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DETERMINATION OF THERMAL NEUTRON CAPTURE GAMMA YIELDS

by

Thomas L. Harper, Jr.
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July, 1969

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Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Sponsored in Part by
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Thomas L. Harper Jr.

Submitted to the Department of Nuclear Engineering on July 15, 1969, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

A method of analysing Ge(Li) thermal neutron capture gamma spectra to obtain total gamma yields has been developed. The method determines both the yields from the well resolved gamma peaks in a spectrum as well as the gamma yields from the unresolved gamma lines which appear in the continuum portion of a spectrum. Accounting for the unresolved continuum enables a large fraction of total emitted energy to be observed, and values of 100% ± 15% are obtained for the cases studied. The techniques used involve the determination of a peak response function suitable for the Ge(Li) pair spectrometer spectra being studied. The response function is used to strip off the effects of the peaks upon the background and unresolved data continuum. The continuum, which is due only to the unresolved lines, is broken into energy bins of 250 keV width and the gamma yield per bin is calculated. Results of the analysis and normalized yields are given for the rare earth samples of: Nd, Sm, Eu, Gd, and Er. The capture data were obtained by using the MITR 4TH1 irradiation facility operated with a Ge(Li) pair spectrometer.

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TABLE OF CONTENTS

Table of Contents (Continued) Page

Table of Contents (Continued) Page

LIST OF FIGURES

List of Figures (Continued).

List of Figures (Continued)

LIST OF TABLES

List of Tables (Continued)

List of Tables (Continued)

List of Tables (Continued)

List of Tables (Continued)

1. INTRODUCTION

1.1 Preface

Nuclear level studies and neutron shielding calculations need information about the number and energy of gamma rays emitted following thermal neutron capture. Basic knowledge about nuclear levels and their properties can be obtained from such data. The nuclear engineer also desires this data for shielding calculations. The purpose of this study is to obtain the radiative capture data that is needed for the above calculations. To do this, a spectral analysis method is developed to study thermal neutron capture gamma spectra obtained from a Ge(Li) detector.

The development of Ge(Li) detectors has greatly improved the technique for measuring thermal capture gamma spectra. Ge(Li) detectors have comparable or better resolution than other gamma spectrometers for gamma energies greater than 1.0 MeV, and they usually have higher efficiency. In addition, Ge(Li) detectors can cover practically the entire capture gamma energy range from 200 keV to 10 MeV, which makes possible much faster data acquisition rates.

To obtain capture gamma spectral data, Ge(Li) detectors can be operated directly, without any coincidence gating, or they can be operated with coincidence gating in either a Compton suppression mode or in a pair spectrometer mode. Both of the latter two modes are used to reduce the background

continuum seen in the spectral data over what it would be if the detector were operated directly.

Recent data taken with a Ge(Li) pair spectrometer at MIT to study thermal neutron capture reactions have shown that in many cases the gamma spectra so obtained are not completely resolved. In such cases the resolved lines are superimposed upon a continuum. The continuum is due in part to the unresolved, low intensity, capture gamma lines from the sample, and in part to background from various sources. The magnitude of the continuum depends upon the sample being studied.

In the cases of well resolved spectra, the gamma lines observed account for all of the energy emitted by de-excitation of the product nucleus. However, in many spectra the resolved lines account for only a small fraction of the emitted energy. In these cases a continuum much larger than expected from background sources is observed.

The spectral analysis method of this study treats both the resolved gamma lines and the continuum portions of spectra obtained with the Ge(Li) pair spectrometer in order to obtain a more accurate estimate of the amount of radiated energy seen per capture in a sample. The spectral data used in this thesis is that obtained from the 4TH1 external sample gamma spectrometer of the MIT Reactor. This spectrometer is similar in principle to the 9CH2 gamma

spectrometer designed by Orphan, and used as a Ge(Li) pair spectrometer. (O-1). Iron, beryllium, and rare earth samples were run in the 4TH1 facility to obtain spectra that would be useful in developing the spectral analysis method. The data from these samples are presented in this study.

Before the 9CH2 gamma spectrometer was shutdown, it was used by Rasmussen and Hukai to obtain thermal neutron capture spectra on 74 elements. These spectra were analysed for their well resolved gamma lines using a computer code developed by Inouye, and the results presented in report MITNE-85. (R-1). The spectral analysis method developed in this work can be applied to the data used in obtaining MITNE-85.

1.2 Review of Instruments Used to Study Capture Gamma Rays.

Table 1.1 summarizes the performance characteristics of the principle instruments used in the study of thermal neutron capture gamma rays. Prior to 1958 the most accurate and detailed results were obtained with magnetic pair and magnetic Compton spectrometers. (G-1, G-2, M-1). The diffraction spectrometer has also been used in the gamma energy range up to 3 MeV. (G-2, M-1). Measurements with these instruments were carried out with natural elements targets usually weighing a few hundred grams. Small quantities of separated isotopes have been used with these instruments with the resolution of 2% at 1.0 MeV being obtained. Two disadvantages of the above instruments are:

Table 1.1 Summary of Performance of Principal Instruments Used to Study Capture Gamma Rays

Instrument	Energy Range	Resolution	Efficiency [a]	Ref. [b]
Magnetic Compton Spectrometer	0.3 MeV - 12.0 MeV	Low 2% High 0.6% at 1 MeV 0.3% at 2 MeV	10^{-5} - 10^{-7}	G-1 G-2 M-1
Magnetic Pair Spectrometer	3.0 MeV - 12.0 MeV	1% - 2%	10^{-5} - 10^{-7}	B-1 G-1 M-1
Diffraction Spectrometer	0.030 MeV - 3.0 MeV	0.1% at 0.1 MeV 1.0% at 1.0 MeV	10^{-5} - 10^{-7}	G-2 M-1
Scintillation Spectrometer	0.03 MeV [c] - 12.0 MeV	20% at 0.1 MeV 6% at 1.0 MeV	10^{-1} at 1.0 MeV	E-2 G-2 G-3
Ge(Li) Spectrometer	0.03 MeV [c] - 12.0 MeV	1% at 0.1 MeV 0.2% at 1.0 MeV 0.08% at 8.0 MeV	10^{-2} at 1.0 MeV 10^{-3} at 4.0 MeV	E-2 T-1 O-1 A-1

a Efficiency in units of counts per gamma quantum incident on the spectrometer.

b Main references for capture gamma data are Nuclear Data Tables:
Vol 3 Nos. 4-6 Dec 1967 from Z=1 to Z=46 (ND-1)
Vol 5 Nos. 1-2 Nov 1968 from Z=47 to Z=67 (ND-2)
Vol 5 Nos. 3-4 Feb 1969 from Z=68 to Z=94 (ND-3)

c Higher energy operation carried out as a pair spectrometer.

(1) their relatively low efficiencies of 10^{-5} to 10^{-7} counts per incident gamma quantum, which require that the sample be placed near the reactor core and that large samples be used, and

(2) the effective energy range covered by these spectrometers which is only part of the energy range in which capture gammas are usually found.

NaI(Tl) scintillation detectors have found application in both direct use and in a pair spectrometer to study capture gamma rays. (E-2, G-2, G-3). Their improved efficiency and wider energy range of operation are advantages over the magnetic spectrometers. However, their poorer resolution restricts their usefulness in studying complex gamma spectra. They have found wider applications in experiments using coincidence, angular correlation, and linear polarization techniques, and for measuring the degree of circular polarization of gamma rays following capture of polarized neutrons. (ND-1, ND-2, M-1, B-2).

The development of Ge(Li) detectors has greatly improved the technique for measuring thermal capture gamma spectra. Ge(Li) detectors have comparable or better resolution than other spectrometers as shown in Table 1.1 for gamma energies greater than 1.0 MeV. The diffraction spectrometer shows the best resolution at gamma energies below 100 keV. The Ge(Li) spectrometer has the advantage of having much greater efficiency than the other high resolution spectro-

meters. Ge(Li) detectors have been used directly to study capture gamma ray spectra (T-1) and have also been used in gamma-gamma coincidence experiments to study capture gamma spectra. The report by Arnell (A-1), which describes a facility using internal reactor targets, and the previously cited work by Orphan, which describes the MIT Ge(Li) pair spectrometer using samples external to the reactor (O-1), demonstrate their use in coincidence experiments.

As mentioned in Table 1.1 the most comprehensive, recent references available for capture gamma data results are those of Nuclear Data. (ND-1, ND-2, ND-3). These references list the energy and intensity values of the gamma lines seen from thermal neutron capture in natural element samples, and in separated isotope samples where results are available.

1.3 Unresolved Gamma Continuum

In some cases, almost all of the capture gamma rays from a sample have been resolved. These cases are characterized by the gamma spectra having a fairly even background level in the energy range 1 to 4.5 MeV. For example, the beryllium and iron pair spectrometer spectra are shown in Chapter 4, Figures 4.4 and 4.6.

In contrast, certain of the elements studied show a large unresolved continuum region in the spectrum. The neodymium spectrum of Chapter 5, Figure 5.2 is an example

in which the gamma peaks are shown to be well resolved and distinct above 5 MeV, whereas at lower energy they merge together and lose identity in the spectrum.

A more extreme case is that of the samarium spectrum of Chapter 6, Figure 6.2, which shows a large unresolved continuum region. Only a few peaks are distinguishable in the spectrum, and a large continuum is observed in the gamma energy range 1.5 to 4.5 MeV. The fractions of observed gamma rays for these elements, as calculated in MITNE-85 are: beryllium 99.4%, iron 91.3%, neodymium 36.7%, and samarium 19.4%. The missing gamma ray energy for the latter two cases is in the unresolved continuum.

To estimate the magnitude of that part of the continuum due to capture gamma rays, it is necessary to determine the shape and size of these contributions. These measurements included using the 4TH1 Ge(Li) pair spectrometer:

(1) to determine the shielding background for triple coincidence operation,

(2) to run iron and beryllium samples to determine the efficiency and peak response functions of the system,

(3) to determine the effect of the triple coincidence timing and window width settings upon the efficiency and the continuum seen in a spectrum, and

(4) to determine the effect of collimator size upon detector solid angle, the continuum, and the peak response function of the detecting system. In general emphasis was

placed upon studying the factors that control the shape of the peak response function and the continuum background.

The results of the above measurements were then used to develop the computer code GAMABC. GAMABC analyses the unresolved continuum region of a pair spectrometer spectrum and estimates the amount of unresolved capture gamma ray intensity that is located in this continuum.

1.4 Format of the Thesis

The next chapter describes the 4TH1 external irradiation facility and the gamma spectrometer. Chapter Three describes the empirical measurements and computer code development needed for studying the resolved peaks and unresolved continuum of a spectrum. Chapter Four presents the results on beryllium and iron and compares them to other published data. The background of the system is also discussed. Chapters Five, Six, Seven, Eight, and Nine give the results for neodymiun, samarium, gadolinium, europium, and erbium samples respectively. Each of these chapters shows the spectra, and lists the run parameters, gamma energies, resolved line intensities and unresolved energy bin intensities of the gamma rays, and fraction of gamma rays seen. The particular samples used were chosen because they present a variety of cases each having a region of unresolved continuum. Chapter Ten gives a summary of results and the conclusions and recommendations for future work. The appendices elaborate

upon certain portions of the analytical techniques used, with Appendices A through E discussing the accuracies of the various calculated parameters, and Appendices F through H discussing the sensitivity, output tables, and Fortran IV listing and input data for the GAMABC code respectively.

2. EXPERIMENTAL APPARATUS

2.1 4TH1 External Irradiation Facility

The spectrometer built by Orphan using the 9CH2 port of the MIT Reactor was replaced by a permanent facility which uses the 4TH1 tangential port. Basic concepts as developed by Orphan were used in constructing the facility. (O-1). Modifications were made in designing the shielding to reduce or eliminate some of the background gamma lines present in the 9CH2 facility. The 4TH1 spectrometer is quite compact owing to the use of large, one to two tons, heavy density concrete shielding blocks.

Figure 2.1 shows a drawing of the overall top view of the 4TH1 facility, and its relation to the MITR shielding and core. Included is the companion facility designed for lattice fuel rod irradiation studies by Hukai. (H-3). A graphite scattering plug 3 7/8 inches in diameter and 39 3/4 inches long is placed inside the 4TH1 tangential through port, next to the reactor core. Its purpose is to thermalize and scatter neutrons into the 4TH1 port. A steel collimator, tipped by a protective cadmium sleeve encased in aluminum cladding, reduces the neutron beam diameter to 3 1/2 inches upon exit from the port. A lead plug, encased in 1/16 inch thick aluminum, is placed 19 inches into the steel collimator in order to reduce the gamma flux emerging from the 4TH1 port while not degrading the neutron flux excessively. This was done to reduce the gamma flux impinging on the sample and then scattering into the detector.

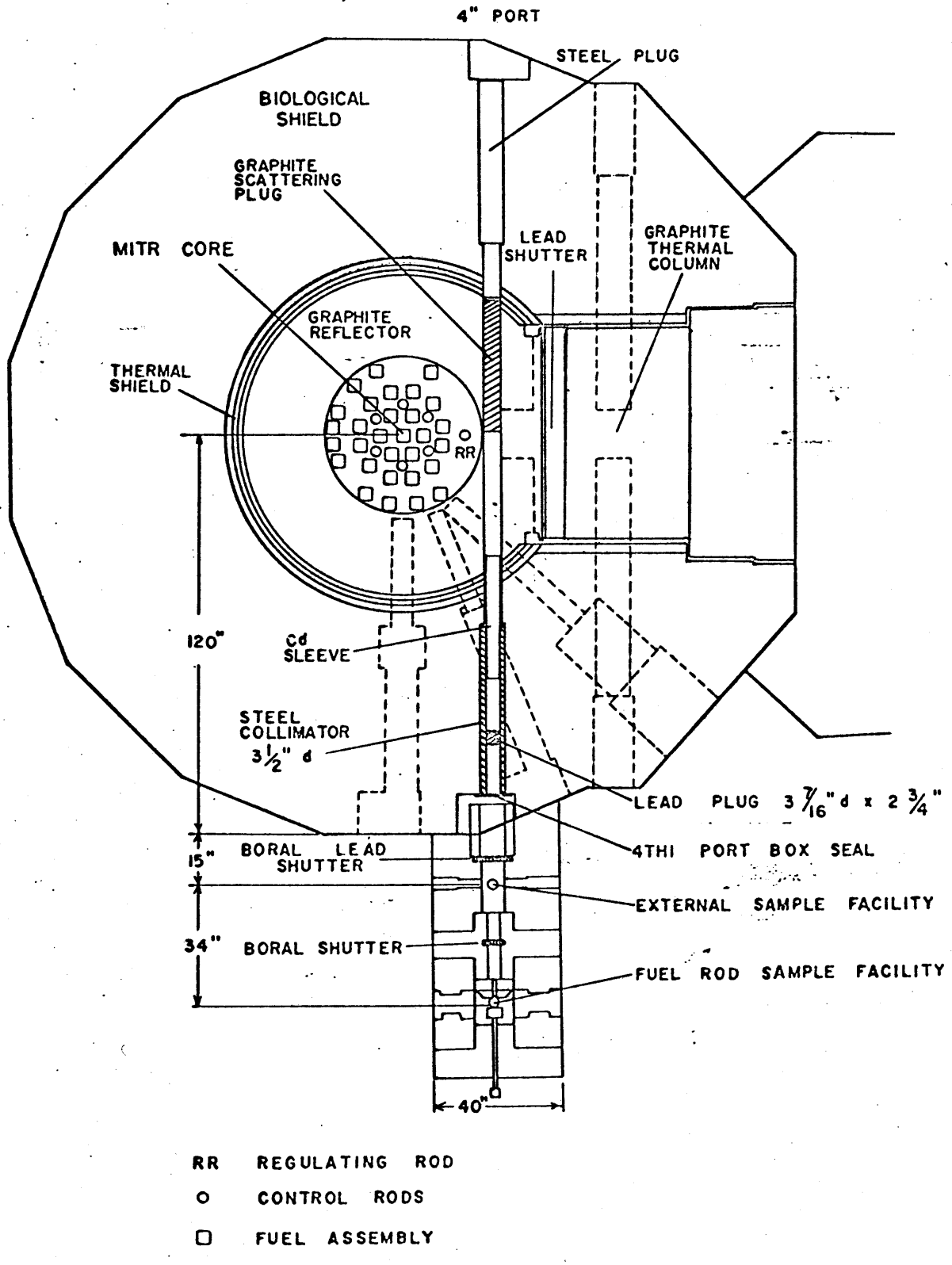

Figure 2.1 Top View of MITR Core and 4THI Irradiation Facility.

A gas seal of 1/8 inch thick aluminum is bolted to the port box exit within the port box and serves to prevent any radioactive gases from escaping. The neutron flight path from the tangential point of the 4TH1 port with the MITR core to the external sample is 135 inches.

Figure 2.2 shows a top view of the 4TH1 facility. An indication of the shielding used is shown by the key in the figure. The primary shielding material used is heavy density concrete, with masonite and boral used liberally to themalize and capture the neutrons being scattered out of the beam. Both steel and lead plugs are used in the acess ports of the facility. A 1/2 inch thick boral - 1/2 inch thick lead shutter may be inserted into the neutron beam, when it is desired to reduce the thermal neutron flux seen by the sample or when the samples are being changed. The lower shielding block fits into the port box by use of a steel cylinder, 12 inches od, 6 inches id, x 13 inches long which is boral and cadmium tipped to reduce neutron leakage between the reactor shield and the facility shield.

Figure 2.3 shows a front view drawing of the external sample facility, indicating the gamma ray flight path. The external sample facility is designed to be able to take a 5" diameter neutron beam from the port, but collimation reduces the actual beam size to 3 1/2" diameter. The

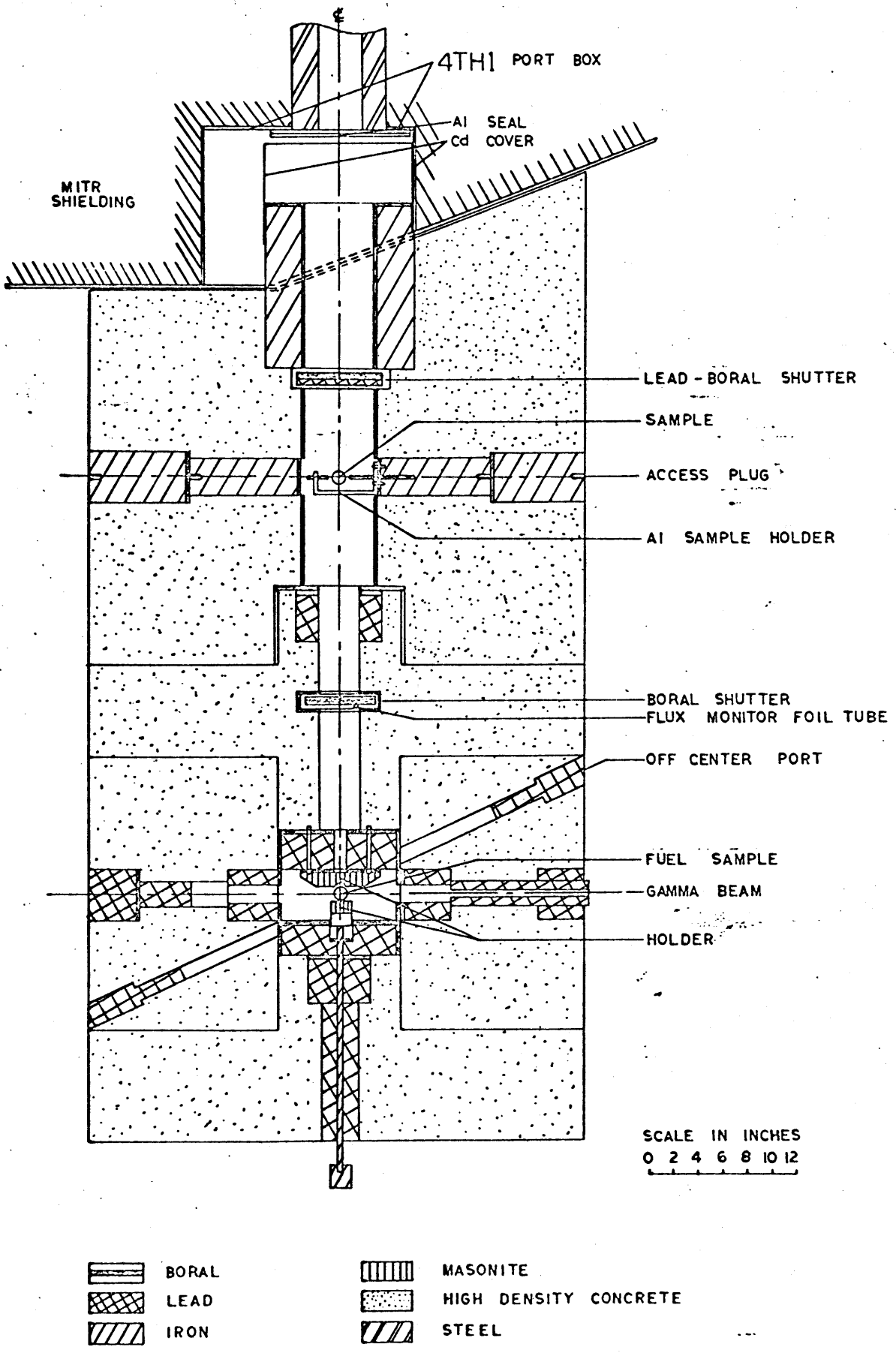

Figure 2.2 Top View of 4TH1 Irradiation Facility.

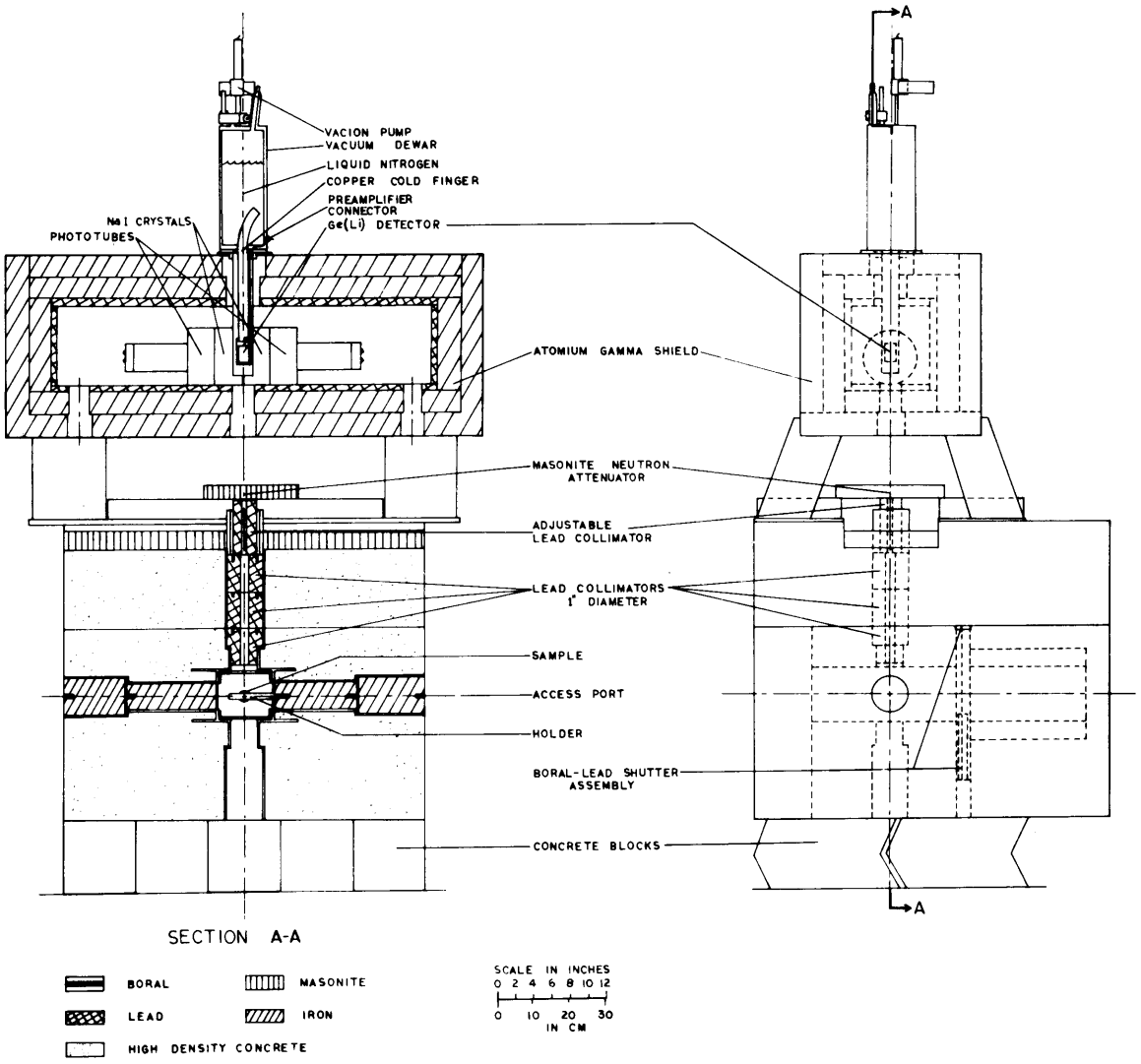

Figure 2.3 Front View of 4TH1 Irradiation Facility Used as a Ge(Li) Gamma Spectrometer.

maximum size of sample studied can be 3 1/2 inches diameter by 5 inches long though usually samples of 1" diameter x 2" length are used. The main shielding along the gamma ray flight path is a 1 1/2" thick masonite plug which is used to scatter neutrons out of the gamma beam. This protects the Ge(Li) detector from unnecessary neutron bombardment.

The gamma beam is defined by a series of 1 inch diameter lead collimators as shown in Figure 2.3. A 6 inch long segment of the lead collimator may be replaced to vary the collimator opening between 3/8 inch and 1 inch. It is shown as the adjustable lead collimator in Figure 2.3. Beyond the sample, the detector sees only the bottom of the shield block which is 13 5/8 inches below the neutron beam in a very low flux region. This helps reduce the neutron induced background seen by the Ge(Li) detector.

The detector and the surrounding NaI(Tl) annulus are placed inside a gamma shield of 5 inches of steel plus 3/4 inches of lead; it was built by Atomium Corp. and has been described by Hanson. (H-4). This Atomium shield serves both as a gamma shield for the detector and as a rigid base for positioning the Ge(Li) detector and NaI(Tl) detectors accurately with respect to one another and to the collimated gamma beam emerging from the sample.

Figure 2.4 shows a photograph of the 4TH1 facility which illustrates the relation of the Atomium shield to

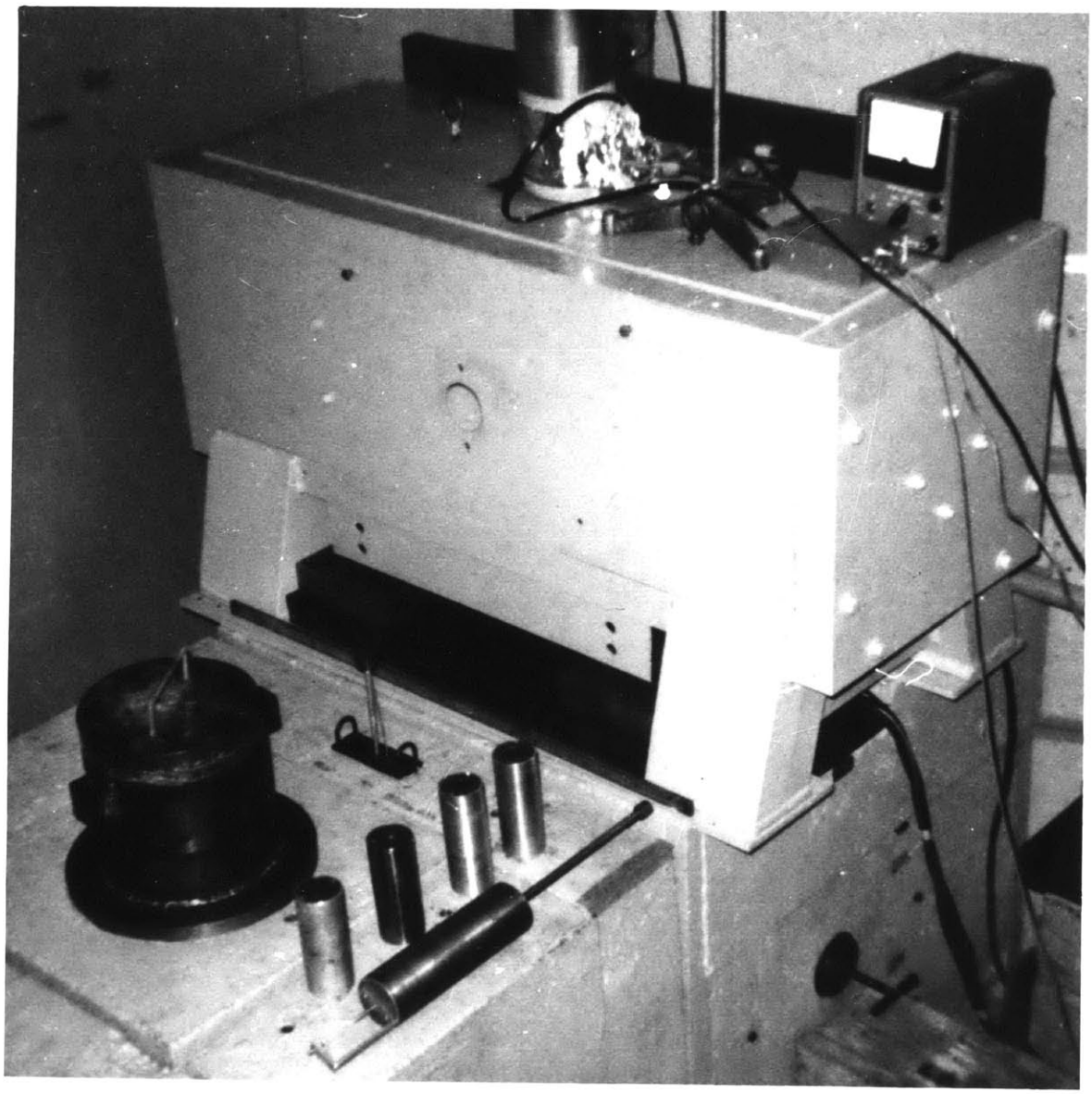

Figure 2.4 Photograph of 4TH1 Irradiation Facility with Shielding Blocks in Place

the shield blocks. Also shown on top of the fuel rod facility shield blocks are the sample holder and plug, and various lead collimators. The Ge(Li) detector's vacuum dewar and preamplifier are shown on top of the Atomium gamma shield.

Figure 2.5 is a photograph of the facility and of the associated electronics used in the data collection. The smaller electronic rack holds the detector electronic systems, and the larger electronic rack holds the 4096 channel analyser.

2.2 Operating Characteristics of the 4TH1 Facility

2.2.1 Sample Geometry

Figure 2.6 shows a photograph of the aluminum sample holder, access port plugs, and various samples that were irradiated in the 4TH1 facility. For studying capture gamma rays, the amount of sample used varied inversely with the effective neutron capture cross section of the sample being studied. Sizes range from about 50 grams for beryllium or iron, to 50 milligrams for samarium. In general, the sample being studied was placed in a poly vial of 1 inch diameter x 2 inch length. In a few cases smaller vials were used.

The samples were positioned by use of the aluminum sample holder that is shown in Figure 2.6. The holder is attached to the boral tipped, steel access plug in the

Figure 2.5 Photograph of 4TH1 Irradiation Facility with Electronic Equipment in Place

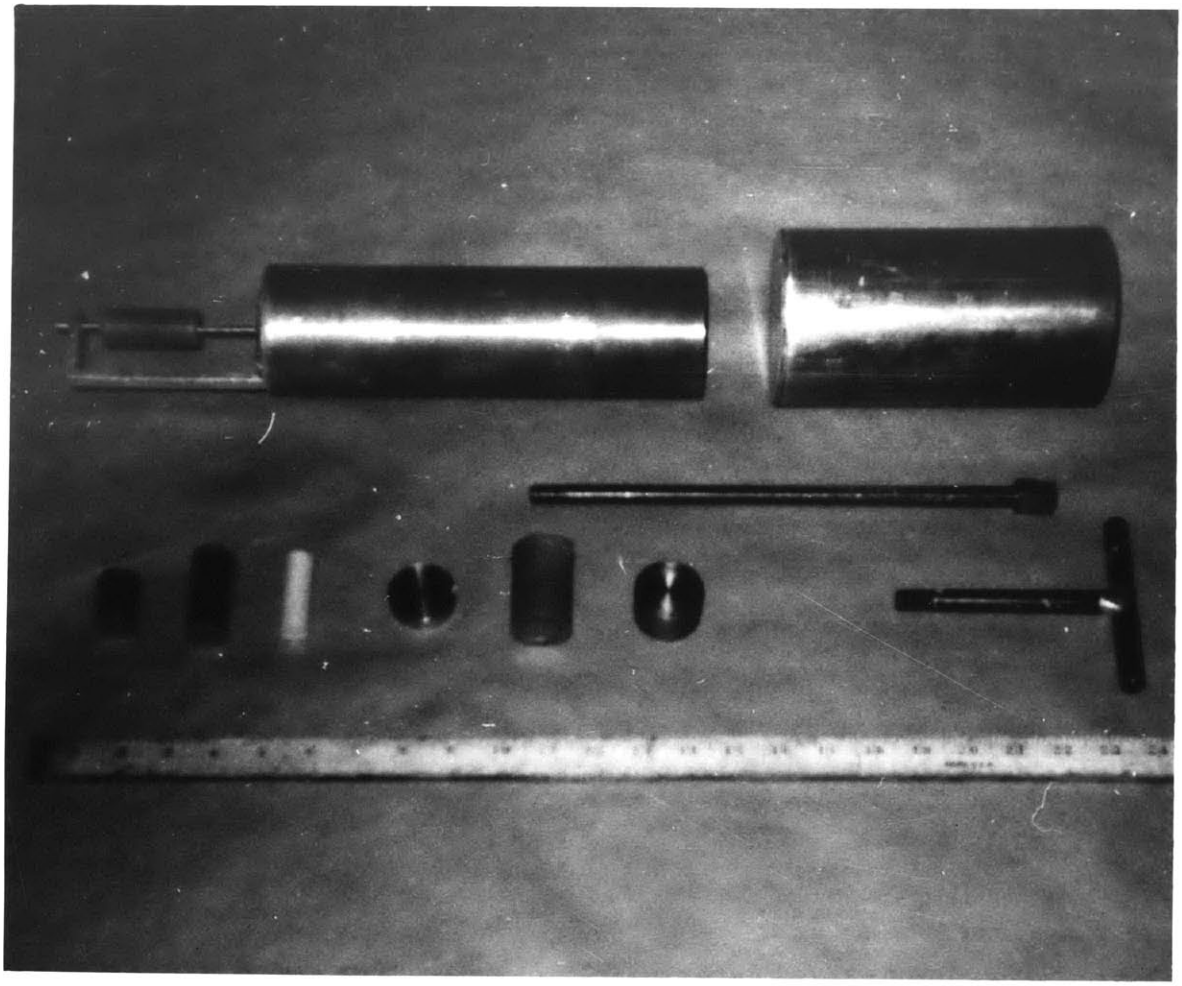

Figure 2.6 Photograph of Al Sample Holder, Access Port Plugs and Various Samples Irradiated in 4TH1 Facility

4 TH1 shield block. Accurate positioning of the steel plug then insures that the holder and sample are positioned in a reproducible geometry. The holder is designed to position the sample in the middle of the neutron beam, while minimizing the amount of holder that is seen by the Ge(Li) detector.

Samples used were more than 99.9% chemically pure. The milligram sample amounts were mixed with pure graphite so as to reduce the flux depression effect in the sample, and to spread the source gammas over the volume of the vial being used. This was necessary so that efficiency and geometry factors determined for the large vial could be used.

2.2.2 Flux Optimization and Determination

From Figure 2.1 of section 2.1, it is seen that there are two components placed in the 4TH1 tangential port that will influence the thermal neutron flux reaching the external irradiation facility. These are:

(1) the position of the graphite scattering plug in the 4TH1 tube, and

(2) the thickness of the aluminum clad, lead gamma attenuator plug whigh is positioned in the steel collimator. The thickness of this lead plug was 2 3/4 inches for the data of this work.

The size of the graphite scattering plug was fixed at 3 7/8 inches in diameter x 39 3/4 inches long. The pos-

ition of the graphite plug was determined experimentally by measuring the neutron flux in the external sample position of the 4 TH1 facility with a bare BF_3 counter. Measurements were made at low reactor power for various positions of the graphite plug. Table 2.1 shows the results.

It is seen from Table 2.1 that the positioning of the graphite scattering plug is not very sensitive in affecting the thermal flux seen in the 4TH1 facility over the range of ±6 inches from position 3. Position 3 indicates the position of the graphite plug for the data used in this work.

The neutron flux in the 4TH1 facility at full reactor power was determined by gold foil activation. Two sets of foils were used. One set was activated in a "known" flux, while the other set was activated in the 4TH1 facility, after being placed on the aluminum sample holder and positioned in the neutron beam. Both beta and gamma activation measurements were used. The gamma ray counting method was preferred because no large correction was required for the foil thickness. In the beta method this correction was substantial. The "known" flux used was that of the 9CH2 spectrometer with a value of 2.8×10^8 ncm^{-2} sec^{-1} with the lead shutter closed. (see Orphan (0-1)). This measurement gave an average value of the flux in the 4TH1 facility of 1.83×10^8 n/cm^2 sec, accurate to ±10% which is adequate for the capture gamma experiment. Even with this flux

Table 2.1

Effect of Graphite Scattering Plug Position Upon the Thermal Neutron Flux in the 4TH1 Irradiation Facility.

No	Position of Graphite Plug (c) Relative to REF(d) (inches)	Relative to Core Tangent (a) Point (inches)	Counting Rate in BF_3 Counter (b) (Counts/10sec)
1.	+ 12 1/2	+23 7/8	51609
2.	+ 6 1/2	+17 7/8	53969
3.	REF	+11 3/8	54356
4.	- 5 1/2	+ 5 7/8	54565
5.	- 13 3/8	- 2	48388
6.	- 16 7/8	- 5 1/2	42763
Background			3203

(a) Measured from mid-point of graphite plug to tangential point of the MITR core and 4TH1 port.
+ means toward 4TH3
− means toward 4TH1

(b) In counting rate per 10 seconds for bare BF_3 counter located in the external sample position of the 4TH1 irradiation facility. MITR power at 250 watts.

(c) Graphite plug of dimensions 3 7/8 inches diameter by 39 1/4 inches long.

(d) REF position defined by edge of graphite plug being 52 inches from step in 4TH1 beam tube.

the Ge(Li) detection system was usually counting rate limited in order to obtain optimum gamma energy resolution. As a consequence, the gamma beam emitted from the capture gamma sample was reduced by using various sized lead collimators placed in the gamma beam. (see Figure 2.3). The sample was then counted for longer times at this lower counting rate. Section 2.4.2 describes the counting rates observed.

The cadmium ratio was measured in the 4TH1 facility and found to be 79. This compares to 580 for the 9CH2 facility, and indicates that a harder neutron spectra is observed in the 4TH1 facility as compared to the neutrons being emitted from the thermal column to the 9CH2 port.

The shape of the neutron energy spectrum affects the cross section value used for the neutron-gamma reaction for capture gamma ray work. In general, Westcott correction values to the neutron capture cross section values (2200m/sec) were used to obtain an effective average capture cross section for the sample being studied. (W-1). The procedure used is the same as that used by Greenwood in his work with capture gamma rays. (G-3). Thus:

$$\sigma_{capt} = \sigma(2200\ m/sec)_{capt}(\ g + r\ s) \qquad (2.1)$$

where g and s are tabulated by Westcott for the element being studied. σ_{capt} is the effective capture cross

section, $\sigma(2200\text{m/sec})_{capt}$ is the capture cross section for 2200 m/sec neutrons, and r is the epithermal index factor indicating the non-Maxwellian shape of the neutron spectrum at the sample. For the 4TH1 facility, r was calculated to be 0.017.

2.3 Ge(Li) Gamma Spectrometer

Generally the same technique as described by Orphan (O-1) were used in fitting a Ge(Li) gamma spectrometer to the 4TH1 irradiation facility. This was done in order to have a system that would closely resemble the 9CH2 Ge(Li) gamma spectrometer which was used to obtain capture data for 74 elements listed in MITNE-85. For this reason the spectral analysis methods developed in Chapter 3 are also applicable to that data. The same Ge(Li) detector, 45, was used for the gamma detector in the 4TH1 facility and was surrounded with the same NaI(Tl) annulus detectors to enable operation in Compton suppression and pair spectrometer modes.

A number of changes and improvements over the system described by Orphan have been made. These include the incorporation of a new preamplifier and amplifier system to the Ge(Li) detector. The detector and electronics were optimized to obtain as high and stable a gamma energy resolution as possible. This involved thermal cycling of the Ge(Li) detector, re-performing a cold clean up

drift on the detector, and the changing of some of the time constants used in the detector pulse shaping before using the analyser to analyse the pulse amplitude.

2.3.1 Free Mode Operation

There are three possible methods of operation of the spectrometer in the detection of gamma rays: direct or free mode, Compton suppression, and pair spectrometer. The free mode method of operation, which was not used extensively for the results in this thesis, consists of using the detector and its associated electronics to drive the analyser. No gating of the analyser is done, and no coincidence or timing of the detected pulses is carried out.

Figure 2.7 shows the schematic diagram of the free mode operation of the Ge(Li) detector. The free mode method of operation is simple to carry out, and requires less electronic equipment than the other two modes of operation. However, it gives high backgrounds because of Compton scattering events taking place in the detector with less than full energy of the gamma ray being deposited in the active region of the detector. Also at gamma energies above 1.022 MeV, the pair production threshold, there can appear three distinct peaks for each gamma ray energy. The full energy peak, single escape peak, and double escape peak are the result of 0, 1, or 2 annihilation quanta escaping the active region of the detector. These peaks which

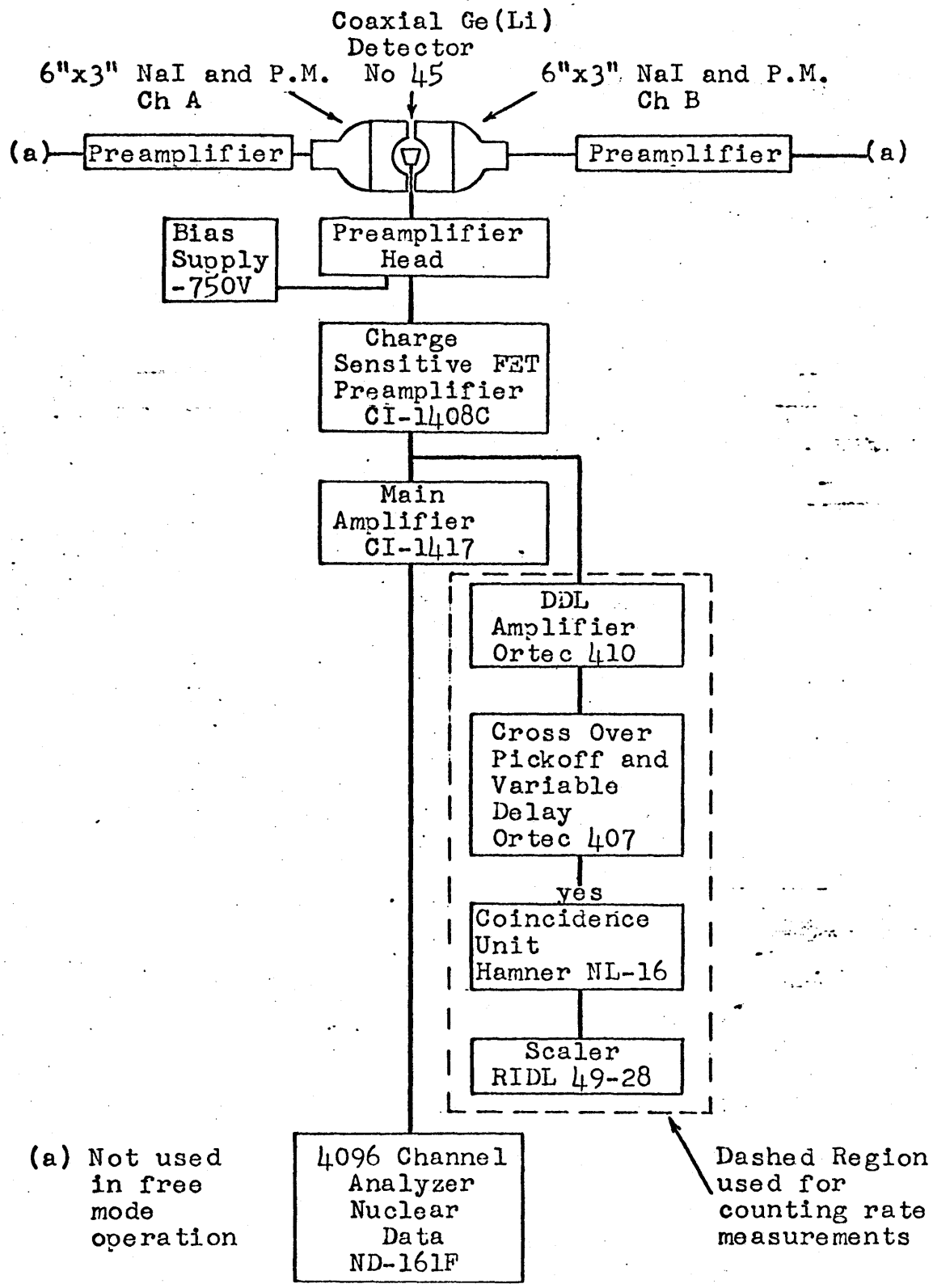

Figure 2.7 Block Diagram of Electronics for Operation in the Free or Direct Mode.

have different efficiencies considerably complicate the analysis of high energy spectra.

2.3.2 Compton Suppression Operation

To solve some of the problems presented by free mode operation, two other modes are used. The Compton suppression mode is used in the low energy gamma ray region of 200 keV up to 3.5 MeV. Its primary purpose is to reduce the amount of continuum background seen in the spectra. This is accomplished by an anti-coincidence mantle using pulses produced by the NaI(Tl) annulus surrounding the Ge(Li) detector to gate the analyser off.

Figure 2.8 shows the block diagram of the Compton suppression system with the electronic components used. There are two NaI(Tl) detectors that surround the Ge(Li) detector and which are out of the direct gamma beam. If a gamma ray is Compton scattered in the Ge(Li) detector the scattered gamma ray escapes. Then less than the full gamma ray energy has been deposited in the Ge(Li) detector. If the scattered gamma ray is detected by one of the NaI(Tl) detectors the analyser can then be gated off by coincidence between the Ge(Li) detector and the NaI(Tl) detector, so as to prevent the Ge(Li) detector pulse from being analysed in the multi-channel analyser.

Figure 2.8 shows the Ge(Li) detector output being amplified by the CI-1408C preamplifier , CI-1417 amplifier,

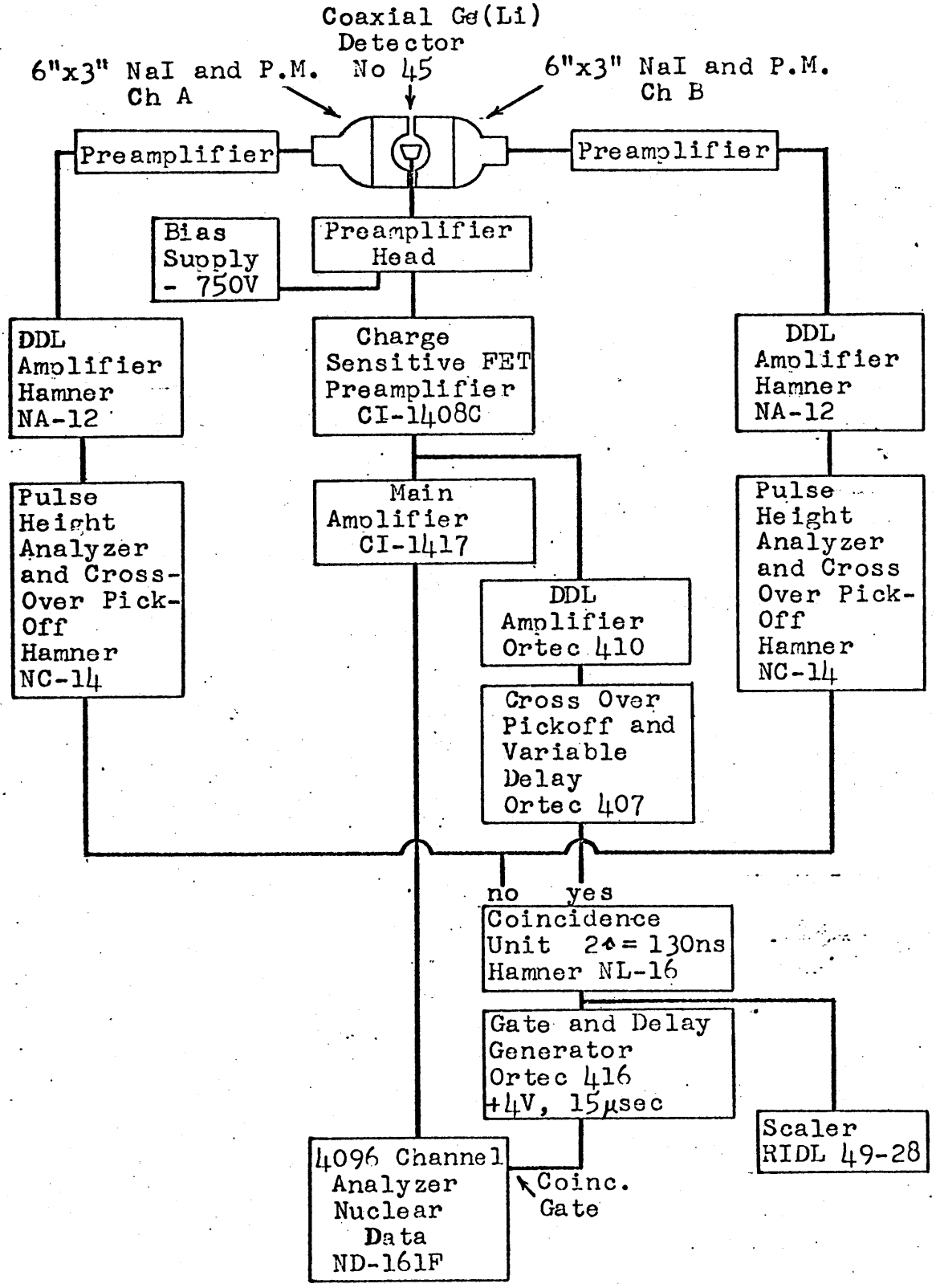

Figure 2.8 Block Diagram of Electronics for Operation in the Compton Suppression Mode.

and then being fed into the ND-161F 4096 Channel analyser. The analyser is controlled by a gating pulse which arrives from the Hamner NL-16 coincidence unit and from the Ortec-416 Gate and Delay generator. Since the analyser has an internal delay of 2 microseconds, the gating pulse must start within this time period if the Ge(Li) pulse is to be analysed. The NL-16 coincidence unit is fed by the Ge(Li) detector pulse in the "yes" mode, and by an analyser pulse from either of the NaI(Tl) detectors in the "no" mode of the NL-16. Thus for the NL-16 to trigger the analyser on, the Ge(Li) detector must have recorded an event, while at the same time neither of the NaI(Tl) detectors has recorded an event.

The DDL Ortec 410 Amplifier and Ortec 407 cross-over pickoff and variable delay generator adjust the timing of the Ge(Li) detectors pulse to coincide with the NaI(Tl) detector pulses. These latter pulses are amplified with the DDL Hamner NA-12 Amplifiers and analyzed with Hamner NC-14 single channel pulse height analysers (operated in integral mode for the Compton suppression mode) & a cross-over pickoff, and variable delay generator were incorporated in these pulse height analyzers).

For long runs the Nuclear Data 502 spectrum stabilizer is used to stabilize upon a high energy gamma peak in the spectrum in order to compensate for gain shifts during

the run. A RIDL 49-28 scaler monitors the gating pulse counting rate which is driving the analyser.

In general the effect of the Compton suppression mode is to reduce the continuous background in the spectrum to about 1/2 the value it would be in a straight free mode run without significantly reducing the efficiency of the full energy peak.

2.3.3 Pair Spectrometer Operation

The third mode of operation uses the Ge(Li) detector as a pair spectrometer. This type of operation was used extensively to study the capture gamma rays with energies between 1.5 MeV and 10.0 MeV. There is an energy region of overlap between the Compton suppression mode and the pair spectrometer mode in which the results of the two methods can be compared.

The principle of operation of the pair spectrometer mode is to record only the double escape peaks of the gamma rays which have undergone pair production. The way this is done is shown schematically in Figure 2.9. Section AA shows the incoming gamma ray undergoing a pair production event in the active region of the Ge(Li) detector and creating an electron-positron pair. The event is analysed if both the electron and positron are stopped within the active region of the detector without losing energy by brems-strahlung radiation which escapes the detector, and if the

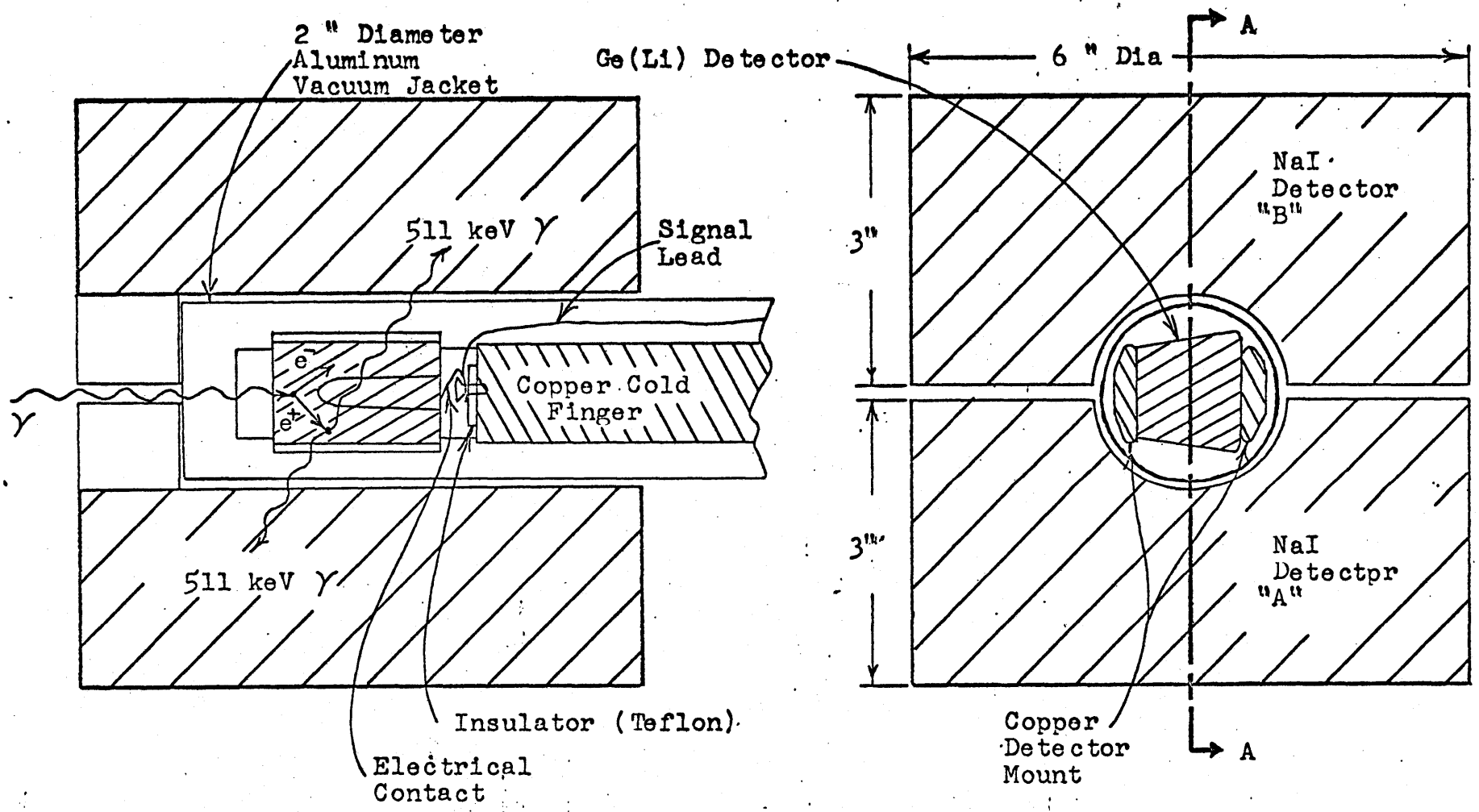

Figure 2.9 Schematic Showing the Orientation of the Ge(Li) Detector between the two NaI Crystals.

quanta produced by the annihilation of the positron both escape the Ge(Li) detector and are then detected by the NaI(Tl) detectors. The requirement of having three simultaneous events leads to designating the pair spectrometer mode as triple coincidence operation.

Figure 2.10 shows the block diagram for the electronics used in the pair spectrometer mode. To accomplish operation as a pair spectrometer each NaI(Tl) detector is set to record only annihilation gamma rays of 511 keV energy. If a coincidence is observed between a detected Ge(Li) pulse and each of the NaI(Tl) detected annihilation pulses, there is a high probability that the event registered in the Ge(Li) detector is a desired pair produced event which has deposited an energy in the Ge(Li) detector of 1.022 MeV less than the full energy of the gamma ray causing the event.

The basic electonic components used in the pair spectrometer operation are the same as those used for the Compton suppression mode. The main difference is that the two NaI(Tl) detectors are now set to record only annihilation quanta by having the two single channel analysers in the differential mode set to cover the annihilation quanta events. Each single channel pulse height analyser output is then fed to the Hamner NL-16 coincidence unit, now operated in the triple coincidence mode. The timing

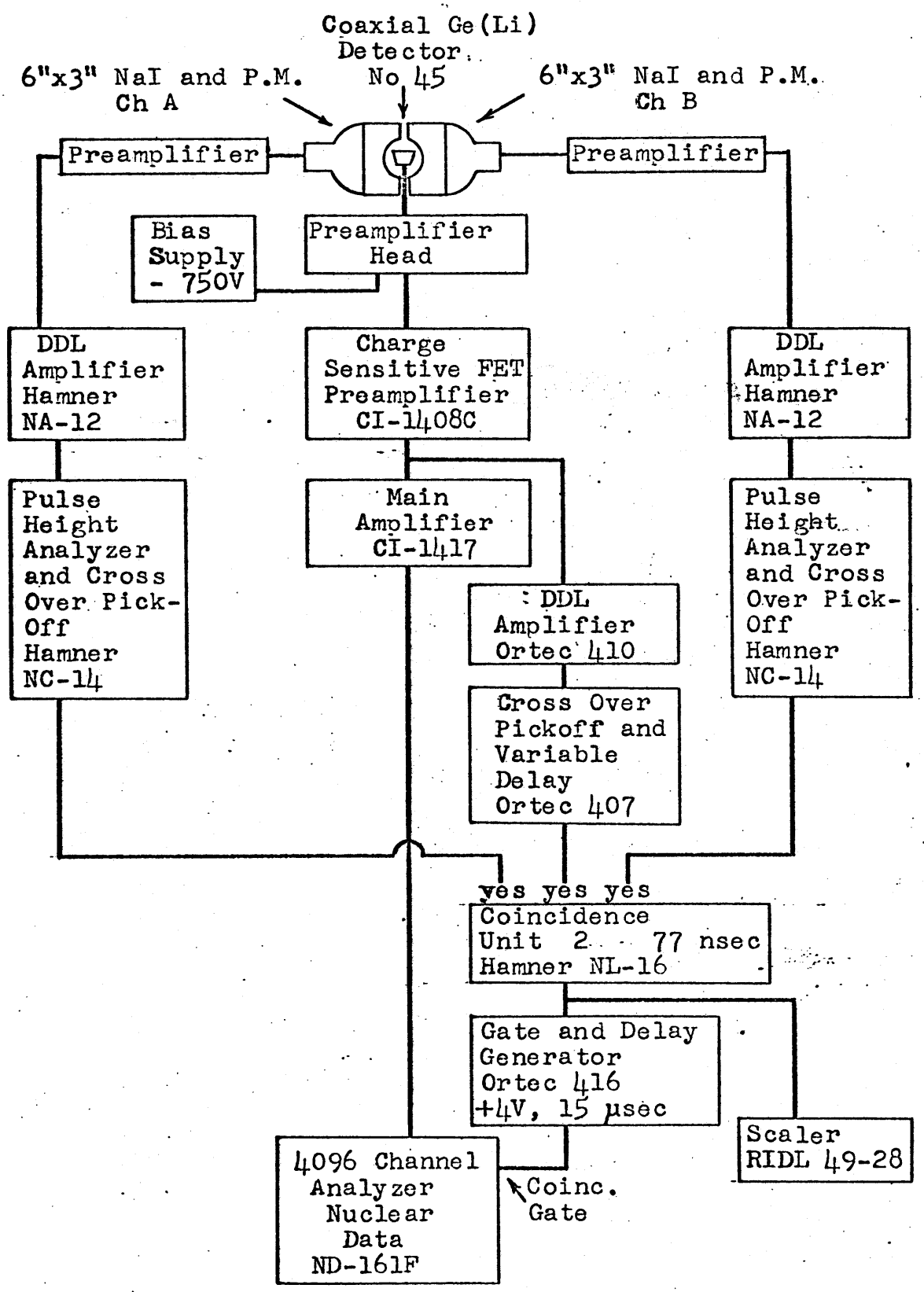

Figure 2.10 Block Diagram of Electronics for Operation as a Pair Spectrometer.

of the pulses remain the same as set in the Compton suppression mode.

The advantage of the pair spectrometer mode of operation is that only one peak is observed for an incoming gamma ray, and that the background continuum is quite low and flat over the entire energy range being studied. A disadvantage is that there is a decrease in efficiency.

2.4 Operating Characteristics of Gamma Spectrometer

2.4.1 Ge(Li) Detector and System Energy Resolution

The main gamma ray detector used in this work was Ge(Li) detector No. 45, which has been described by Orphan. (O-1). The shape of the detector is trapazoidal with dimensions of 27 mm x 36 mm x 40 mm. It was produced by using the one-ended coaxial drift method, and has an outer dead layer of 2 mm thickness, and an inner p-type dead region of 9.5 mm x 17.5 mm. These give an active volume of 21.7 cc. The relatively large dead regions, and non-uniform shape of the detector at the gamma ray impinging end of the detector are definite disadvantages to the overall efficiency of the system. However, detector No. 45 was used because: (1) it was the detector used to obtain the capture gamma data that was analysed in MITNE-85, and (2) it provided a better high energy resolution and a higher efficiency at gamma energies

greater than 4 MeV than was obtainable with other detectors available.

The detector was operated at liquid nitrogen temperature with a reverse bias of -600V to -750V. The exact bias voltage was determined by optimizing the resolution. The resolution obtained varied from a full width at half maximum, FWHM, of 4.5 keV for gamma energies less than 1.5 MeV, to 8.0 keV for gamma energies around 8 MeV.

The resolution is dependent upon many factors. The most important of which are:

1. Electronic noise in the detector, preamplifier, and amplifier.
2. Stray or ground loop pick-up in the electronic components.
3. Statistical fluctuations in the number of electron-hole pairs produced in the detector.
4. Electronic instabilities (i.e., gain and/or zero shifts) during the data collection.
5. Counting rate limitations on the Ge(Li)-electronic system which result in a loss of resolution at high counting rates.

The first factor was treated by optimizing the operating bias of the detector so as to obtain as high a resolution as possible while still keeping the leakage current low across the detector. A high operating bias

also cleaned-up the shape of the gamma peaks observed in the gamma spectra. The capacitive loading of the preamplifier by this Ge(Li) detector (No 45) was 77 pf.

Factor two was accounted for by checking for external ground loop problems and stray pick-up problems for each data run. Usually it was sufficient to have a solid ground between the detector and the preamplifier, and to have adequate shilding on the signal connection between the detector vacuum dewar and the preamplifier head.

Factor Three is inherent in the operation of the detector. Factor Four was treated by using a spectrum stabilizer (ND-502) in the analyser circuit to correct for these instabilities. Factor Five was treated by operating the system at low counting rates, as described in the next section.

2.4.2 Counting Rate Data

In general the Ge(Li) spectrometer is operated to give optimum energy resolution; however, it is known that the energy resolution obtained depends upon the counting rate in the Ge(Li)-electronic system. It was found for this system that counting rates of 10,000 counts per second (cps) increased the FWHM of the gamma peaks by about 1 keV, and that this effect was greater for counting rates above 10,000 cps. For this reason the spectrometer was operated

Table 2.2

Counting Rate Data for Various Gamma

Spectrometer Sample Runs

Run Number	Sample	Type Run[a]	Collimator[b] Inches	Counting Rate[c] Counts per Minute
11071	Fe	PS	1/2	836
12171	Fe	CS	1/2	75608
	Fe	FM (e)	1/2	144027
11141	Be	PS	1	298
11201	Be	CS	1	43499
	Be	FM (e)	1	72333
11151	Sm	PS	1/2	641
12161	Sm	CS	1/2	148720
11191	Gd	PS	1/2	915
11192	Gd	CS	1/2	143471
11211	Nd	PS	1/2	882
11212	Nd	CS	1/2	162578
	Nd	FM (e)	1/2	276559
11213	Eu	CS	1/2	155222
11221	Eu	PS	1/2	765
11261	Er	PS (d)	1/2	1100
11262	Er	CS (d)	1/2	285385
	Background	CS (f)	1/2	21214
11263	"	CS	1/2	19350
11271	"	PS	1/2	150

(a) PS - Pair spectrometer mode, CS - Compton suppression mode, FM - free mode. PS mode operated at 1/2 the gain of the CS or FM modes.
(b) Diameter of lead collimator, see section 2.4.3.
(c) Counting rate from RIDL scaler in cpm as measured by number of gating pulses driving the analyzer.
(d) 3 1/2 inch thick masonite in gamma beam rather than 1 1/2 inch thick masonite used in all other runs.
(e) Free mode data taken with gain settings the same as for the Compton suppression runs for the same element.
(f) Background run taken one week before run 11263.

at counting rates below 10,000 cps. For many of the samples studied, the limiting factor in the experiment was the maximum counting rate that the detector could tolerate rather than the amount of neutron flux available in the 4TH1 facility.

Table 2.2 lists the counting rates in counts per minute used for the various data runs listed in this work. The counting rate values were determined from the RID1 scaler as indicated in Figures 2.7, 2.8 and 2.10. Note, that the scaler was set to count the number of gating pules driving the analyser, and that this is not the counting rate in the Ge(Li)-preamplifier-amplifier system except for the free mode cases.

The counting rate in the Ge(LI)-electronic system was kept below 600,000 cpm or 10,000 cps for all of the samples listed. It is seen that in absolute counting rates, the Compton suppression mode analysed roughly 1/2 of the counts (pulses) going through the Ge(Li) detector and amplifying system. Also it is seen from Table 2.2 that all of the samples except berylliumused the 1/2" diameter lead collimator and were counting rate limited. The beryllium sample used the largest lead collimator diameter of 1" and was flux limited. This is to be expected because of the low neutron capture cross section of beryllium.

2.4.3 Geometry Effects

The counting rate in the Ge(Li) detector can be

adjusted somewhat with the use of different sized lead collimators. Figure 2.3 shows the position of the adjustible lead collimator and also the placement of the masonite slab used to scatter neutrons away from the Ge(Li) detector. Table 2.3 shows the geometry factors that were used for the various sized lead collimators.

TABLE 2.3

GEOMETRY FACTORS

Collimator Size	Factor (dimensionless)
1"	4.15×10^{-5}
3/4"	3.165×10^{-5}
1/2"	1.585×10^{-5}

The geometry factor was determined for the 1" diameter lead collimator by the solid angle in steradians seen by the Ge(Li) detector (area of 5.20 cm^2) at a distance of 1 meter from the sample, divided by 4π steradians.

The geometry factors for the 3/4" and 1/2" lead collimators were determined by an experiment which compared the counting rates seen with these collimators to the counting rate seen with the 1" collimator for the same sample and flux.

It is necessary to know the amount of sample viewed by the Ge(Li) detector when the 1 inch diameter collimator

isused. In the present system, the Ge(Li) detector subtends an area of 5.20 cm^2 at a distance of 1 meter from the sample. The detector sees an entire poly vial of dimensions 1 inch diameter by 2 inches long when viewed end on by the detector through the 1 inch collimator. Samples with diameters larger than 1 3/4 inches are not viewed in entirity, and in such cases corrections for the amount of sample being viewed must be taken into account.

If the sample is misaligned by the sample holder so that it is off center with respect to the Ge(Li) detector, only a portion of it will be viewed. In some cases studied, small mis-alignment caused a correction to be necessary to account for the fraction of the sample viewed. In the presentation of the data, these corrections are so noted.

2.4.4 Absorption Correction Factors

In analysing the data, it is necessary to account for the attenuation of the gamma beam caused by the 1 1/2 inch thick masonite plug in the gamma beam, as well as to account for the self-absorption of the gamma rays within the sample.

The attenuation due to the masonite plug was determinedempirically by measuring the density of the masonite used (ρ=1.31 gm/cc), and the thickness (1 1/2 inches), and the gamma attenuation for mono-energetic gamma rays of energies: 511 keV, 662 keV, 1.17-1.33 MeV, and 2.615 MeV.

The attenuation was determined by using a NaI(Tl) crystal, a gamma collimator, and standard gamma sources. From these measurements it was found that the measured μ/ρ values (for masonite) agreed quite well with those listed for water as given in Evans (E-1). Then using the μ/ρ values for water at other energies, an attenuation curve for the masonite plug for various gamma energies was obtained.

The self-absorption attenuation in a sample was estimated by using the values of μ/ρ as given by Siegbahn (S-1) for materials whose atomic number was close to the atomic number of the sample being studied. An average thickness for the gamma ray path in the sample was assumed to be 1/2 of the total sample thickness in the direction facing the Ge(Li) detector, and the density was calculated from the sample weight and dimensions.

2.4.5 Pair Spectrometer Intrinsic Efficiency

It is necessary to have efficiency curves for each mode of operation in order to relate the number of counts recorded in a gamma peak to the actual number of gamma rays impinging upon the detector. The determination of the detector efficiency curves to be used with the data involves complicated energy effects taking place within the detector. Thus the intrinsic efficiency of the detecting system is determined experimentally. Orphan (O-1) has measured the intrinsic efficiency for the pair spectrometer and Compton suppression modes of operation. Since the same

detector is used for the data in this work, the same efficiency curves apply. However, it was desirable to recheck the efficiency measurement for both modes of operation in order to determine that the system was working correctly, and to check the effects of the various parameters upon the measured efficiency. Thus data were taken with beryllium and iron samples as standards. The beryllium data were analysed with an efficiency curve that was determined by requiring the calculated Be capture gamma peak intensities to agree with the published results for Be. The iron data were analysed using the efficiency curve as determined from the Be analysis, and agreement of the iron results with the published results for iron confirmed that the efficiency curve used was the correct one.

Figure 2.11 shows the result of this measurement for the pair spectrometer mode of operation. The gamma energy listed is for the full energy of the gamma peak, while the efficiency is for the double escape peak. Below a gamma energy of 1.022 MeV, the pair production threshold, the efficiency is zero. In figure 2.11, Orphan's data is shown as a dotted line, the new efficiency curve is shown as a solid line, the ⊙ denote the data points for Be, and the ⊕ denote the data points for Fe data. Both efficiency curves are corrected for the gamma attenuation by external materials which were in the gamma beam, namely the 1 1/2 inch masonite or the 1/2 inch LiF plugs.

It is seen that this work indicates a slightly higher

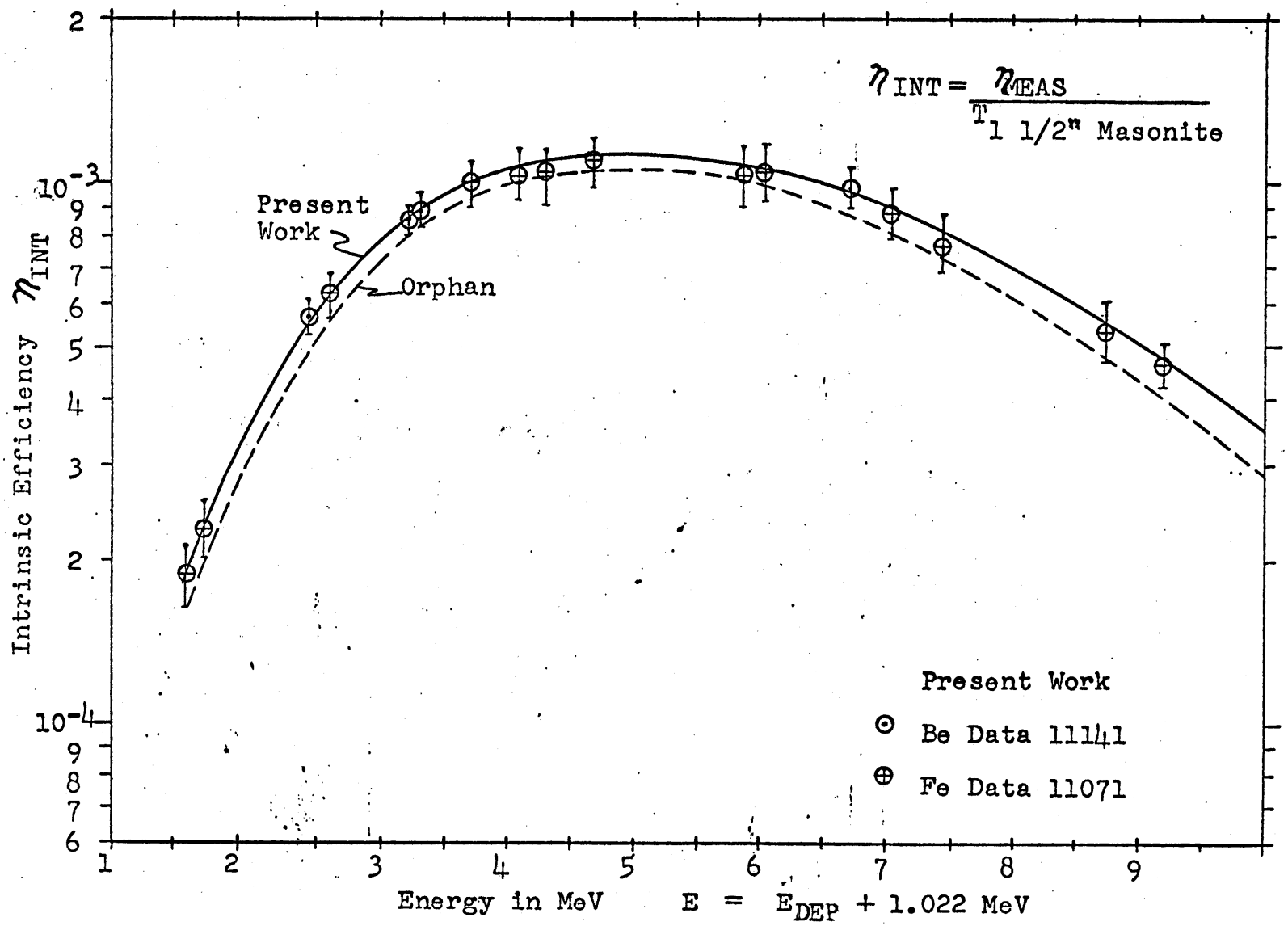

Figure 2.11 Double Escape Peak Intrinsic Efficiency for Ge(Li) Pair Spectrometer.

efficiency value than Orphan obtained. This higher value can be explained by considering the estimated errors associated with either curve. Both measurements are empirical, and thus both reflect uncertainties in the values to which the fit is made, i.e., the published yields for iron and beryllium, and the statistical uncertainties involved in these standard data runs. It is estimated that both of these effects give a combined uncertainty in the relative standard deviation of the curve of about ±10% for the gamma energy range of 2.5 to 9.0 MeV.

A second contribution to the uncertainty in the pair spectrometer efficiency is the efficiency dependence upon the window width settings on the single channel pulse height analysers in the NaI(Tl) circuits, see Figure 2.10. It was observed experimentally that these window width settings affect the efficiency and the background continuum of the triple coincidence spectrum being studied. Narrow windows give decreased efficiency of operation and decreased background, and wide window settings give higher efficiency with increased continuum background in the spectrum. Thus, it is necessary to monitor the response of the NaI(Tl) system to the annihilation quanta before and after a triple coincidence run in order to check that no shift in the window width has occurred, and that the window width setting has not changed.

Table 2.4 shows data on the ThC" 2615 keV double escape peak for various window width settings. Three different window widths were studied: narrow (0.60V, 0.75V) or 1.0 x FWHM of each annihilation peak, medium (1.10V, 1.50V) or 2.0 x FWHM of each peak, and wide (2.10V, 2.50V) or 3.5 x FWHM of each peak. The other parameters such as counting time and sample position were kept the same for each run.

The data of Table 2.4 indicate that the medium window width setting should be chosen as the operating point of the pair spectrometer, since for this setting the peak to background ratio is still high, and the efficiency acceptible. Too wide window setting degrade the peak to background ratio, while too narrow settings decrease the efficiency.

All of the pair spectrometer data presented in this work had medium window settings corresponding to 2 x FWHM of the annihilation quanta in each of the NaI(Tl) detecting systems. The pair spectrometer counting rate was monitored during a data run, and the window width settings were checked before and after each run, so as to be certain that no drift or change has taken place in the settings during a run.

A third contribution that can effect the pair spectrometer efficiency is the resolving time settings in the triple coincidence module. This coincidence unit (NL-16) is shown

Table 2.4

Effect of Window Width Upon Pair Spectrometer Efficiency for ThC" 2.615 MeV Double Escape Peak

Run Number	Type[a]	Window Width[b] Ch A	Ch B	Count Rate (cpm) (c)	Peak/Bkgnd Ratio (d)	(e)	Peak Area[f]	Ratio of Peak Areas[g]
11293	PS	0.60	0.75	45.4	61	200	2131	0.0205
11291	PS	1.10	1.50	188	54	207	8932	0.0854
11292	PS	2.10	2.50	402	38.8	108	13673	0.1305
12021	FM	-	-	330000	4.5	3.9	104601	-

Note: All runs taken for the same ThC" sample, geometry, and run time (live) of 111 minutes. Free mode run 12021 not corrected for analyzer dead time of 20%.

(a) PS - Pair spectrometer run, FM - Free mode run.

(b) Window width settings given in Δvolts. FWHM for 511 keV annihilation peaks in the NaI(Tl) detectors were (0.60, 0.75) Δvolts.

(c) Counting rate given in counts per minute as measured by RIDL scaler counting the gating pulses feeding the analyzer.

(d) Peak height to average background at the peak as calculated by averaging the minima on each side of the peak.

(e) Peak height to average background at 290 keV below the 2615 keV ThC" double escape peak.

(f) Peak area for the 2.615 MeV double escape peak, in counts.

(g) Ratio of PS peak area to FM peak area of run 12021, for ThC" 2.615 MeV double escape peak.

in Figure 2.10. The 2τ resolving time can be varied from 5 to 150 nsec. The resolving time used for data in this work is 77 nsec. which conforms to the 75 nsec. resolving time used in obtaining the data used in MITNE-85.

John (J-1) et. al., have discussed this timing effect upon the efficiency and background for a pair spectrometer similar to the one beingused here. Their results show that a resolving time of only 40 nsec. is required to accept 90% of all true coincidences of the 511 keV gamma rays detected in the two NaI(Tl) detectors, whereas a resolving time of about 80 nsec is required to accept the corresponding Ge(Li) pulses. Consequently one could use a system in which two coincidence units are used. The advantage gained by such a system is that the background continuum is reduced while the double escape peak efficiency remains about the same. Essentially, it is the continuum due to chance coincidences in the two NaI(Tl) scintillators, that is reduced.

2.4.6 Compton Suppression Intrinsic Efficiency

Measurement of the full energy peak efficiency was done for the Compton suppression mode of operation. The full energy peak efficiencies for the iron data were determined so as to give good intensity values with published results on iron.

Figure 2.12 shows the outcome of this measurement. The efficiency curve measured by Orphan (O-1) is shown

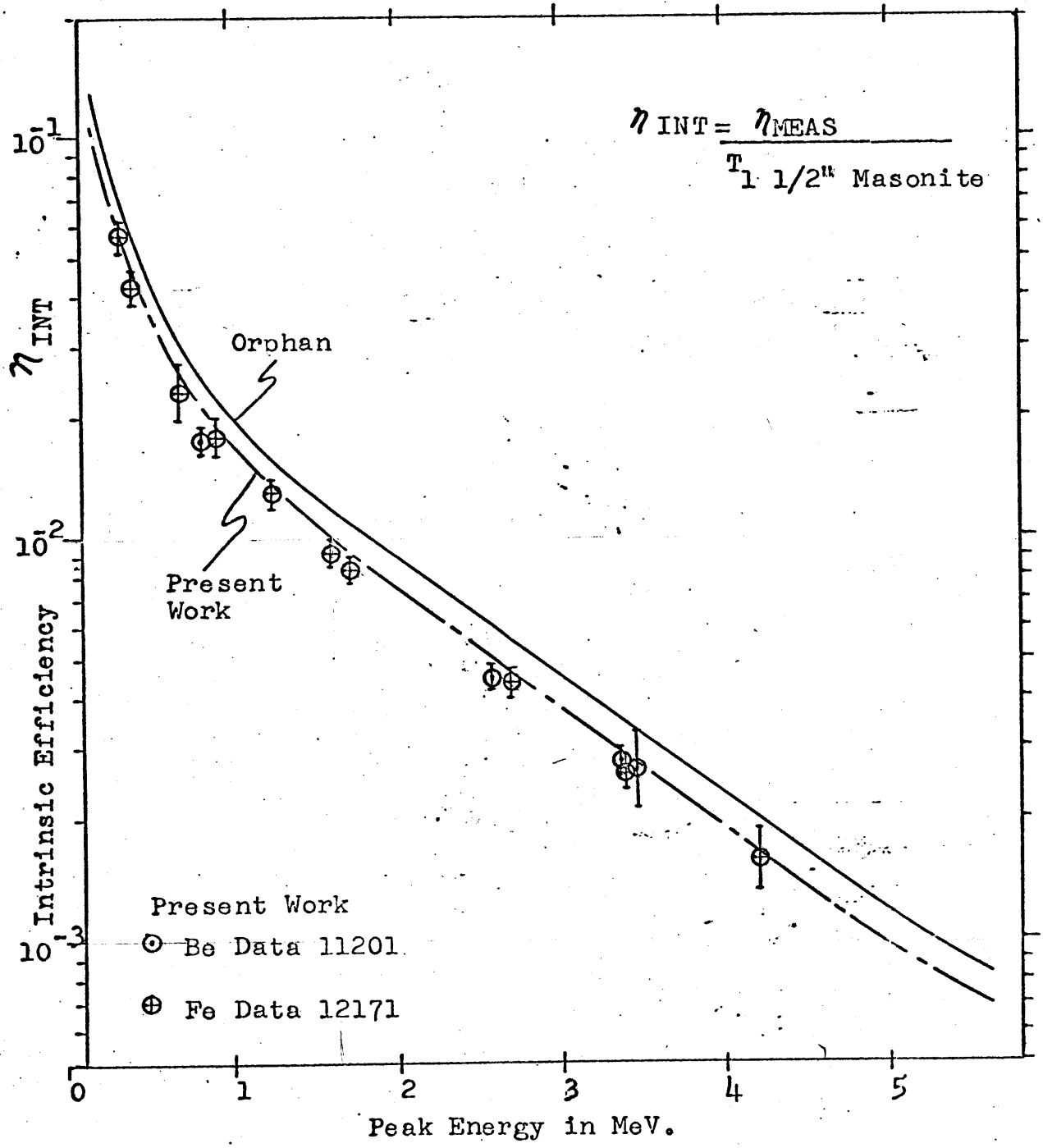

Figure 2.12 Full Energy Peak Intrinsic Efficiency for Ge(Li) Compton Suppression Operation.

as the solid line, and the experimental points show the iron and beryllium data as measured in this work with the uncertainties in each measured point.

The curve of Figure 2.12 is extended to gamma energies of 4 and 5 MeV to allow for comparison with triple coincidence data in that energy range. The percent relative standard deviation of the curve in Figure 2.12 is estimated to be ± 10% in the energy range 400 keV to 3.0 MeV.

2.4.7 Non Linearity Correction

An experimental method is used to check for system non-linearity. This consists of using a pulser connected to the test input of the CI 1408C preamplifier, to simulate a spectrum of many peaks equally spaced in energy (voltage). Analysing such a spectrum gives an indication of the system energy linearity. (O-1, H-5).

The method works well provided that the pulser and voltage triggering source are stable enough so as not to over-ride the effect being measured. Such was the case for the mercury pulser used, whose output amplitude was determined by an EDC Model MV-100 millivolt standard (0-10V output) accurate to 1 part in 10^4.

Usually about 100 equally spaced pulser peaks were recorded for triple coincidence operation ($\sim$2 keV/ch), and 50 peaks for the Compton suppression data ($\sim$1 keV/ch). The peaks were then analysed for energy separation, and

compared against what the separation would be if the system were perfectly linear. This analysis thus produced a linearity correction factor inchannels for each pulser peak.

Figure 2.13 shows a plot of these corrections factors versus channel number obtained for the data used in the later chapters. The linearity curve was determined periodically during the taking of the data, but Orphan showed (0-1), and as found in this work, the linearity correction curve remained essentially the same over several months of data recording.

2.4.8 Energy Calibration Standards

Two accurately known calibration peaks are used to obtain a linear fit between the corrected channel number of the peak center and gamma energy. Table 2.5 indicates the primary and secondary energy calibration standards used in this work. The accuracies of the standards were 1.0 keV or less in all cases. The annihilation and hydrogen capture gamma lines were used in analysing the Compton suppression data. The hydrogen capture line and lead line were used in analysing the pair spectrometer data. In the cases when the lead capture gamma line was not prominent in the spectrum being studied, one standard from the secondary lines 7-11 was used as the high energy calibration peak.

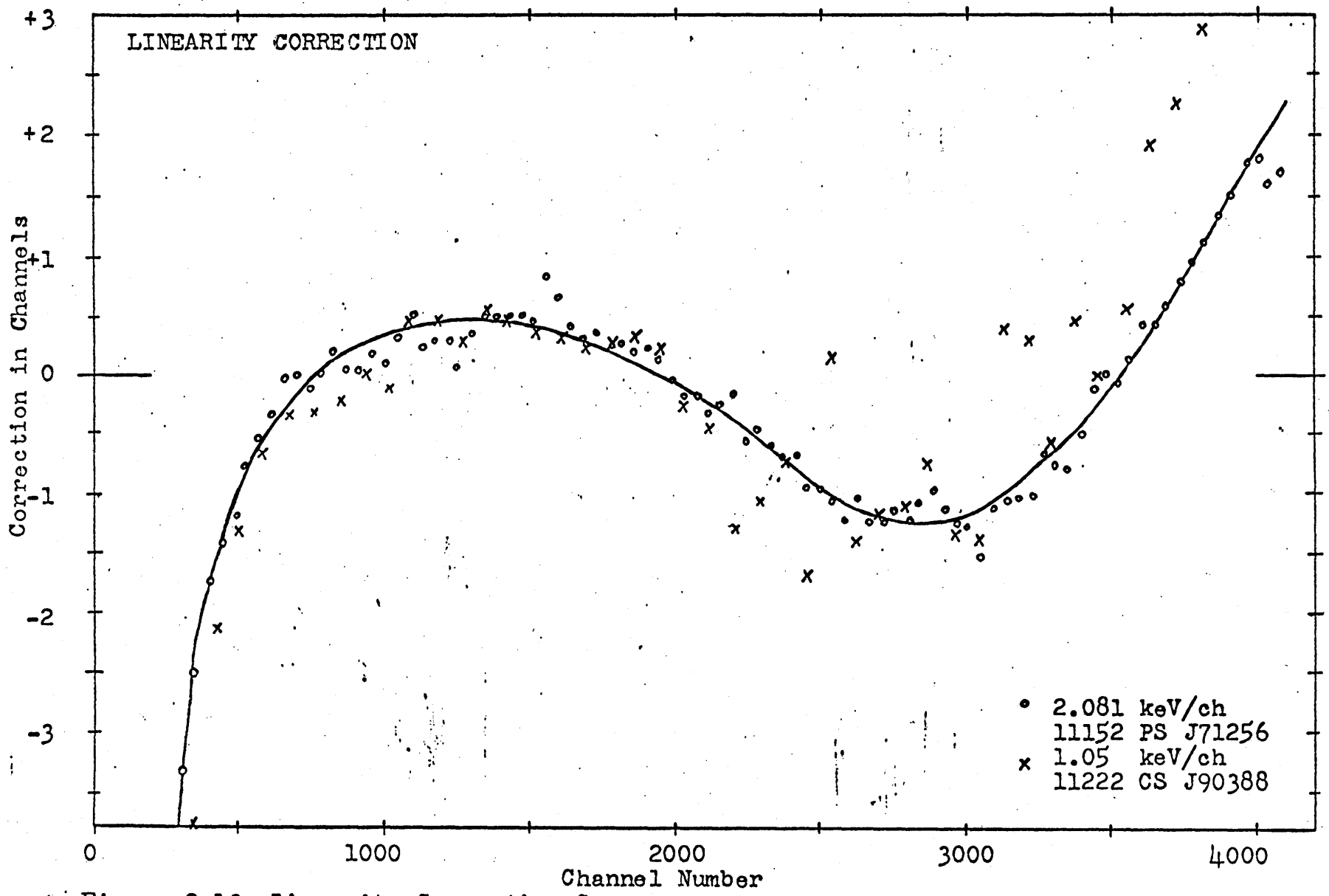

Figure 2.13 Linearity Correction Curve.

Table 2.5

Energy Calibration Standards

	Primary:	Energy (keV)	Reference
1.	Annihilation	511.006 ± .005	(a)
2.	Hydrogen Capture Line	2223.28 ± .15	ND-1, G-5
3.	Lead Capture Line	7367.7 ± 1.0	O-1
	Secondary:		
4.	Argon-41 Beta Decay Line	1293.64 ± .04	W-3
5.	3 x Annihilation	1533.018 ± .015	(a)
6.	Al-28 Beta Decay Line	1778.5 ± 1.0	R-1
7.	Iron Capture Line	6018.2 ± 1.0	O-1
8.	Iron Capture Line	7278.8 ± 1.0	O-1
9.	Al Capture Line	7723.8 ± 1.0	R-1
10.	Cu Capture Line	7915.0 ± 1.0	R-1
11.	Iron Capture Line	9298.4 ± 1.0	O-1

(a) Electron rest mass for 1963 atomic constants.

2.4.9 Comparison of Modes of Operation

As previously mentioned, the main advantages of using the pair spectrometer operation over that of the other two modes are (1) the simplicity of the spectra obtained and (2) the flatness of the background region over the gamma energy span of 1.5 to 9.0 MeV. This flatness of the background continuum enables one to analyse the unresolved part of the spectrum that appears for certain samples. Such an analysis would be almost impossible to perform if only free mode or Compton suppression data were available.

Tables 2.2 and 2.4 have shown typical values of counting rates of pair spectrometer runs versus free mode and Compton suppression mode runs. The efficiency for the various modes is given by Figures 2.11 and 2.12. Based on efficiency alone, it is seen that the Compton suppression mode is the method of choice over the triple coincidence mode for gamma energies below 5.0 MeV. However, for the reasons mentioned above, it is desirable to use the triple coincidence mode to its lower gamma energy limit of 1.5 MeV in order to achieve a much smaller and more uniform background, and to have a less complicated spectrum for analysis.

Galloway (G-4) has indicated a procedure to use in comparing two gamma data collection methods. Both Compton suppression and pair spectrometer modes are compared to free

mode operation, and the conclusion is reached that pair spectrometer operation is not as suitable as the other two methods when its efficiency is too low as compared to its reduction in background.

This is true to the extent that in such cases the sensitivity for seeing weak peaks is less for pair spectrometer operation than for the other methods. However, the advantage gained in simplicity of the spectra and flatness of the background will sometimes outweigh the disadvantage of decreased sensitivity for triple coincidence operation. This is especially true when one is analysing all of the gamma peaks in order to determine the energy levels and also when one is treating the continuum region of the spectrum in order to determine the distribution of the emitted energy.

3. DATA ANALYSIS

3.1 Introduction

This chapter explains the methods used in the analysis of the data obtained from the gamma spectrometer described in Chapter 2. The information desired is the accurate knowledge of the total amount of gamma ray energy emitted per neutron capture as a function of gamma ray energy. To obtain this information it is necessary to determine the energy and intensity of the well resolved gamma lines that are characteristic of the sample being studied and to determine the magnitude of the continuum portion of the gamma spectrum due to weak unresolved capture lines.

The basic recorded data consists of the multi-channel analyser spectrum of the data, usually of 4095 channels. Two spectra are taken to cover the capture gamma energy range. The Compton suppression mode covers the gamma energies from 200 keV to 2.0 MeV, and the triple coincidence mode covers the gamma energies from 1.5 MeV to 10.0 MeV. For both sets of data, linearity measurements, flux measurements, and run time measurements are taken. These are used in the analysis to relate the measured data in channel numbers and counts to gamma energies and intensities.

The Compton suppression spectrum is analysed for the well resolved gamma peaks, and the triple coincidence spectrum is analysed for both the well resolved gamma peaks as well

as the continuum due to the unresolved capture gamma lines.

The well resolved part of the spectrum is analysed to determine the location of the peak in channel numbers, and the peak area in counts. It is then necessary to convert from channel number to energy, and from counts to intensity. The intensity in the case for thermal neutron capture data is expressed in units of the number of gamma rays emitted per 100 captures in the sample.

The continuum part of the spectrum is analysed by calculating the amount of the continuum due to sources other than the unresolved weak gamma lines, and then subtracting off these effects from the observed continuum. The main effects contributing to the continuum other than the unresolved gamma lines are: (1) background from the shielding material of the spectrometer, and from scattered gamma radiation, (2) low energy counts due to the response of the detector to a higher energy resolved gamma rays, and (3) low energy counts due to the response of the detector to higher energy unresolved gamma rays. If each of the above effects is adequately accounted for, and the results subtracted from the observed continuum, the amount left will be due to only the unresolved capture gammallines. This is then analysed by breaking the remaining continuum into conveniently sized energy bins, and determining the number of counts in each bin. This number is converted to an equiv-

alent gamma intensity value using an average gamma energy for the bin.

It is also desirable to obtain an estimate of the errors in the listed values of the gamma ray energies and intensities for the capture data. Uncertainties in various calculational assumptions and empirical values contribute to the error, in addition to the usual statistical uncertainties in the basic recorded data.

Two computer codes were written to perform the analysis. Computer code GAMANL, which has been described in MITNE-97, is the main code which performs the gamma analysis on the well resolved peaks of the spectrum. (H-1). Computer code GAMABC, which is described in this work, is the code which: (1) uses GAMANL to analyse the resolved peaks in the spectrum, (2) analyses the continuum portion of the spectrum, and (3) determines the fraction of emitted gamma energy seen in the spectrum data.

GAMABC is used only with the pair spectrometer data because the complexity of the continuum background in Compton suppression or free mode data precludes its use in such cases. Although, in principle, GAMABC could be used with any spectral data provided one was able to input to the code the correct information about the composition of the continuum due to background and peak response effects characteristic of the system.

3.1.1 Fourier Smoothing of Data

A main feature of computer code GAMANL is that it smooths the spectral data before analysing the gamma peaks in the spectrum. This is done in order to facilitate the data analysis as well as to filter out the non-relevent noise fluctuations in the data spectrum. A Fourier transformation is performed on the 4095 discrete data points of the spectrum. The transformed data is smoothed by an appropriate filter function, and an inverse Fourier transformation is performed on the filtered data. The resulting smoothed spectrum is analysed by GAMANL.

Report MITNE-97 describes the use of this smoothing technique and indicates the choice of filter function to be used. Hamawi (H-2) describes the effect of smoothing in reducing the statistical errors in the calculated results over what they are for unsmoothed data.

3.2 Energy Calculation

To obtain the energy of a spectral peak, it is necessary to determine the center of the peak in channel number, and to convert this value to energy. This conversation must take into account any system non-linearities.

The peak center in channel numbers is obtained by fitting a parabola to the three channels which have the highest counts/channel. The point of zero slope on the parabola is determined and recorded as the peak center.

The value so obtained is found to be accurate to ± 0.2 channels, as per the work of Orphan. (O-1). Since a typical channel width is 2 keV/ch, this corresponds to an accuracy of energy to about ± 0.4 keV. However, non-linearities and uncertainities in the calibrations standards result in a decrease in the over all accuracy of the energy value of the gamma line to about ±1.0 keV. Here the accuracy quoted is expressed as the standard deviation to be expected in the energy value.

To account for system non-linearities, a linearity check is performed periodically on the system using the method described in Section 2.4.7. The linearity correction curve is used to correct the center of the peak in channel numbers as measured in the spectrum, to what it would be if the system was perfectly linear. The correction value used is determined from a second order interpolation using the three values of the linearity correction curve that are nearest to the channel number that is to be corrected.

After the correction for the system non-linearity has been applied, the energy of the gamma peak is determined by using two of the calibration standards described in Section 2.4.8. The corrected peak centers for the two calibration standards are determined and a linear fit is used to convert from channel number to energy for the peak being studied.

3.3 Area Calculation

In addition to locating the center of the peak in the spectrum, it is necessary to calculate the number of counts in the peak (i.e., the peak area). To do this a background level upon which the peak is situated must be determined. After subtracting this background from the recorded, smoothed data, two methods are used to obtain the peak area: the summation method, and the Gaussian method.

3.3.1 Background Determination

The background under a peak is determined by a linear fit between two appropriately averaged minima on each side of the peak. Figure 3.1 illustrates the method used to determine the background level under a peak, and the linear fit used to approximate this background. The data of Figure 3.1 are that of the 2589.5 keV line of Be., pair spectrometer operation, run number 11141.

The computer code GAMANL defines a peak as the region between two minima in the spectrum. The code searches for the minima in a spectrum by starting at the low energy end of the data at a lower channel number limit designated as IMAX which is read into the computer. This limit indicates the maximum number of channels to be bypassed before starting analysis of the data, and thus bypasses low energy noise and the analyser threshold region of the spectral data.

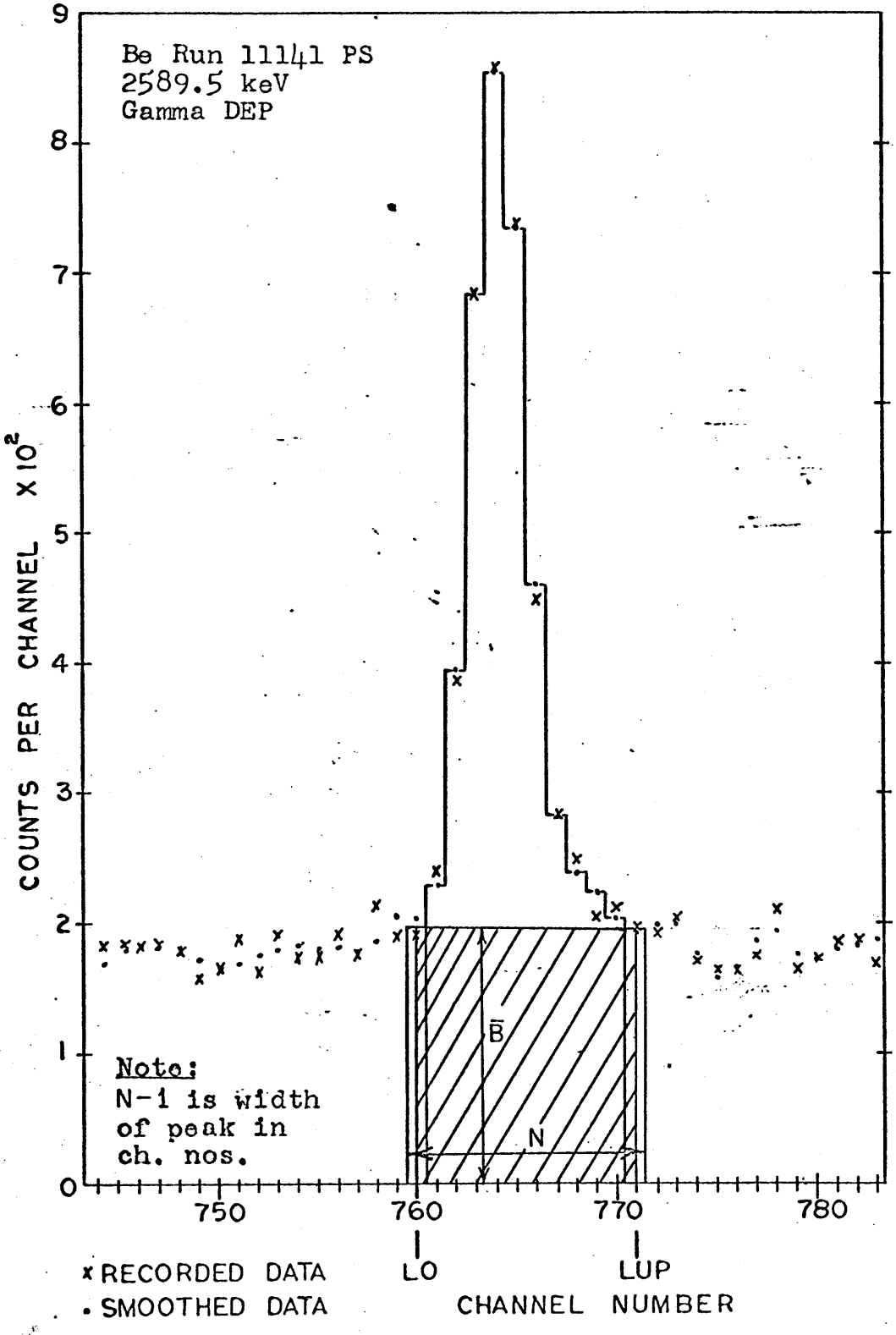

Figure 3.1 Background Determination for a Resolved Peak.

Each succeeding minimum point is compared to the previous minimum accepted (after averaging) as a background point. This is done to assure that a reasonably continuous background is maintained, and to eliminate the possibility of peak multiplets interferring with the calculation of the background level under a peak. The criterion used is given in Equation 3.1:

$$\text{NEXT MIN} \leq \text{LAST MIN} + 10.0 + \text{DCR} \times \sqrt{\text{LAST MIN}} \qquad (3.1)$$

where NEXT MIN is the minimum point being studied in counts/channel, LAST MIN is the last minimum point accepted and averaged as a background point in counts/channel, and DCR is the factor which controls the range the minima are allowed to vary. DCR is read into the code, and usually has a value of 1.0 to 3.0 depending upon the data being studied. If this criterion (equation 3.1) is not satisfied the minimum point in question is ignored and the code searches for the next minimum value at a higher gamma energy.

After a minimum is accepted as satisfying the DCR criterion, points around it are averaged with it so that the averaged value will better approximate the background at a minimum point. However, points near the minimum that are too far above the minimum point in counts/channel must be rejected by an exclusion criterion or the averaged value

would not be a good indication of the background. This exclusion criterion is that in order for a point having Y counts/channel to be averaged with a minimum, Y must satisfy Equation 3.2:

$$Y \leq \text{NEW MIN} + \sqrt{\frac{\text{NEW MIN} + \text{LAST MIN}}{2.0}} \qquad (3.2)$$

where NEW MIN is the counts/channel of the minimum point being averaged, LAST MIN is the counts/channel of the last accepted minimum point after averaging with points near it. The square root function is to approximate one standard deviation variation in the averaged points. The number of points (channels) near the minimum points used in this averaging is an input parameter to the code, and usually has the value of 7.0 signifying a possibility of averaging at most the nearest 3 channels on each side of the minimum point.

Once the minima on each side of the peak are determined and averaged, the background under a peak is determined by a linear fit between the two minima points. This is shown as the solid line in Figure 3.1 from the low energy channel number, LO, to the high energy channel number, LUP. Subtracting the calculated background from the original smoothed data yields a region composed of the gamma peak.

This region is then searched to assure that the peak has a suitable peak height, and if so the location of the peak is stored and the peak is later analysed for energy

and intensity. This is done by finding the maximum point in count/channel between the two minima of the peak. The maximum value, which is approximately the peak height, must satisfy Equation 3.3 if the peak is to be analysed. Equation 3.3 is:

$$\text{PKHT} \geq \text{BGER} \times \sqrt{\frac{\text{NEW MIN} - \text{LAST MIN}}{2.0}} + 10.0 \qquad (3.3)$$

where PKHT is the maximum value in counts/channel between the two minima, NEW MIN and LAST MIN are as defined for Equation 3.2, and BGER is the factor which controls the magnitude of the peak heights analysed as indicated. The BGER factor is an input parameter to GAMANL, and is usually 2.0 or 3.0.

In some situations peak multiplets are encountered. This situation is described in Section 3.3.4. In such cases the BGER criterion is applied to each maximum point encountered between the two minima.

After the three criteria, of Equations 3.1 to 3.3 are performed, the next minima at higher energy is searched for and the process repeated until the entire spectrum is analysed. Performing such an averaging and fitting procedure yields a[1] spectrum composed only of the gamma peaks, and another[2] spectrum composed only of the background, the weak peaks rejected and the unresolved gamma continuum portion of the spectrum, if there is any.

3.3.2 Summation Method

After the background level has been determined for the region under a peak, a straight summation of the counts/channel for channel numbers from the lower minimum to the upper minimum will yield the peak area plus background area. The background area is then subtracted off by multiplying the base of the peak in channel numbers by an average background value in counts/channel. Equation 3.4 using the notation of Figure 3.1 indicates the method:

$$\text{AREAS} = \sum_{I=LO+1}^{I=LUP-1} \text{DATA}(I) + (1/2)\,(\text{DATA}(LO)+\text{DATA}(LUP)) - (N-1)\,\bar{B} \qquad (3.4)$$

where: AREAS is the peak area by the summation method in counts, DATA(I) is the counts/channel in the Ith channel, LO is the channel number of the peak minimum on the low energy side of the peak, LUP is the channel number of the peak minimum on the high energy side of the peak. The summation is taken from I = LO + 1 to I = LUP - 1. The 1/2 factor accounts for the fact that only one half the counts at channel numbers LO and LUP can be attributed to the gamma peak, being studied and one half of the counts go to the neighboring peak. N is equal to LUP - LO + 1, and N - 1 is equal to the base of the peak in channel numbers. $\bar{B}$ is the average background under the peak in

counts/channel.

Equation 3.4 is the basic area calculation equation for the summation method. An error analysis is performed upon Equation 3.4 in Appendix A.

3.3.3 Gaussian Method

A second method of calculating the area under a peak is that of the Gaussian method. It consists of assuming the peak is a Gaussian curve in shape situated on a linear background. References on treating a gamma peak as a Gaussian curve can be found in works by Helmer (H-6) and Hamawi (H-2). The area under a Gaussian curve is given by its height and variance as:

$$\text{AREAG} = \text{PKHT} \times \text{VARIANCE} \times F \times \sqrt{2\pi} \quad , \qquad (3.5)$$

where AREAG is the area of the peak in counts for the Gaussian method of calculation, PKHT is the peak height of the peak in counts/channel, above the background level, VARIANCE is the variance of the Gaussian curve that fits the gamma peak, in channels, F is a factor that corrects for the slight non-Gaussian shape of the peak,

It is useful to relate the variance of the Gaussian curve to its full width at half maximum, FWHM, in channels. The relation is:

$$\text{FWHM} = 2 \times \text{VARIANCE} \times \sqrt{2 \ln_e 2} \quad ,$$

or

$$\text{FWHM} = 2.355 \times \text{VARIANCE} \quad . \qquad (3.6)$$

Using Equation 3.6 in Equation 3.5 gives:

$$\text{AREAG} = \sqrt{2\pi} \,/\, (2 \sqrt{2 \ln_e 2}) \times F \times \text{PKHT} \times \text{FWHM} \quad ,$$

or

$$\text{AREAG} = 1.0645 \times F \times \text{PKHT} \times \text{FWHM} \quad . \quad (3.7)$$

Equation 3.7 is the basic equation that gives the peak area in counts using the Gaussian method of calculation. The peak height is calculated by fitting a parabola to the three channels of the peak having the highest counts/channel after background subtraction. After the parabola is determined, the peak height is calculated as the value of the parabola at the maximum point, i.e., the point of zero slope.

The FWHM of a peak is determined by performing a least squares on the FWHM of all of the singlet peaks in a spectrum, to a second order equation in gamma energy (MeV). This enables the FWHM of any peak to be calculated at any gamma energy in the spectrum by using the least square parameters so determined. It also reduces the uncertainty in the FWHM value since all of the spectrum peaks are being used to obtain it and not just one.

The shape factor F is calculated by comparing both methods of area analysis for strong, well resolved, singlet peaks. F is the factor calculated which makes the Gaussian area agree with the summation method area for the strong

peaks. F was found to range from 0.98 to 1.10 depending upon the data being studied.

Appendix B performs an error analysis upon the Gaussian method area Equation 3.7, and Appendix C discusses the use of both methods of area analysis.

3.3.4 Analysis of Partially Resolved Peaks

The background determination and peak location methods will sometimes pick up partially resolved peaks. This will occur when a measured minimum value between two peaks is too large to be accepted as a background point in the spectrum. This is determined by the DCR criterion described in Section 3.3.1. Figure 3.2 illustrates such a case for doublet data, where the minimum point at Channel 3192 is rejected by the DCR criterion and the background is shown by the solid line in the Figure.

The GAMANL code treats doublets and triplets in its analysis. For doublet analysis two Gaussian curves are fitted to the data, and the area within the doublet is divided according to the ratio of the two corrected peak height values in the doublet. Similarly, for triplet analysis, the area in the triplet is partitioned according to the magnitude of the three corrected peak heights composing the triplet. For peak multiplets of greater than third order, the code picks out the three strongest peaks in the multiplet according to the counts/channel values of the peak

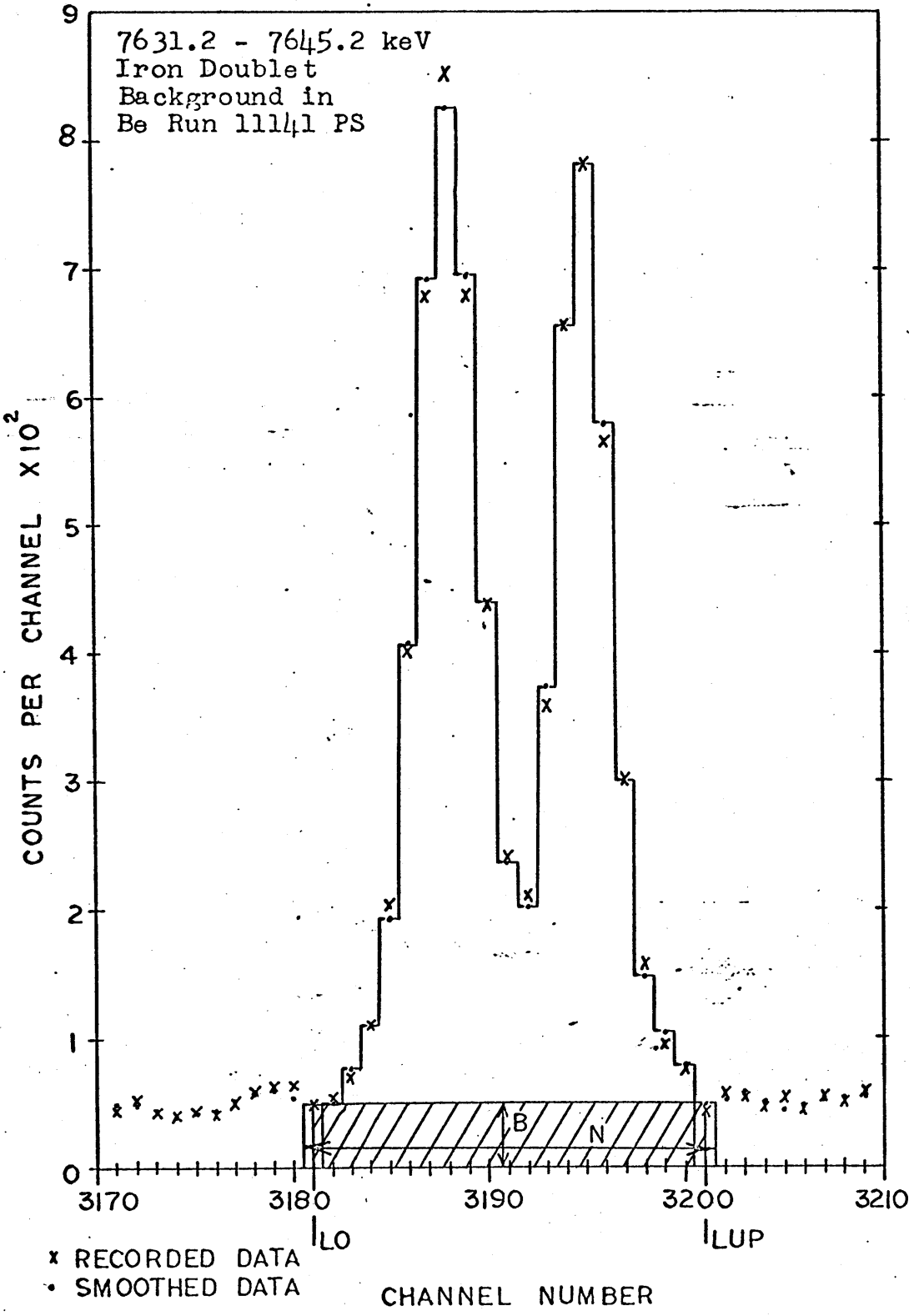

Figure 3.2 Background Determination for a Gamma Doublet.

maxima, and then treats the multiplet as a triplet.

3.4 Intensity Calculation

Once the area under a gamma peak has been determined in counts it must be converted to a physical value that is determined by the nature of the experiment being performed. The value that is of interest in these capture gamma experiments is the intensity of the gamma line expressed in number of gamma rays of a given energy emitted per 100 thermal neutron captures in the sample. The relation between the area of the peak and the intensity is given by the following equation:

$$INT = \frac{AREA}{Eff(E)\ Tsa(E)\ Tma(E)\ g\left(\frac{F_2 N \sigma_c F_1 \phi\ t}{100}\right)} \quad ,(3.8)$$

where: INT is the intensity of the gamma peak of energy E in number of gammas of energy E emitted per 100 thermal neutron captures in the sample; AREA is the gamma peak area in counts observed, as calculated from the recorded spectrum; Eff(E) is the intrinsic efficiency of the detecting system to gamma rays of energy E at the surface of the Ge(Li) detector, in counts/number of gammas. Its value depends upon the mode of operation being used. Tsa(E) is the correction factor for self absorption of gamma rays of energy E in the sample; Tma(E) is the correction factor for attenuation of gamma rays of energy E by the masonite,

or any other material placed in the flight path of the gamma beam from the sample to detector; g is the geometry solid angle correction factor that is dependent upon the lead collimator size being used, and the sample to detector distance. The last term in parenthesis in the denominator is the total number of thermal neutron captures divided by 100 experienced by the sample during the data run. F_2N is the total number of atoms in the sample being studied, that are viewed by the Ge(Li) detector; σ_a is the average effective thermal absorption cross section in cm^2 for the element being studied; F_1 is the flux depression factor for the sample being studied; ϕ is the average thermal neutron flux observed at the outside edge of the sample during the run, in neutrons/cm^2 sec; t is the time in seconds during which the spectrum was collected.

Equation 3.8 is the basic equation that is used to relate the area of a peak to the intensity value of the gamma line. For computer analysis it is convenient to re-write Equation 3.8 in a slightly more compact form. This gives:

$$INT = \frac{AREA}{EFF \quad SANGLE \quad FLUXT}, \tag{3.9}$$

where: EFF represents the energy dependent terms of Equation 3.8; SANGLE is the geometry solid angle factor, g, of Equation 3.8. FLUXT is the total number of thermal

neutron captures divided by 100, experienced by the sample during the data run.

The next sections describe the calculation of the denominator terms of Equation 3.8. Appendix D gives an error estimate in the calculated intensity value.

3.4.1 Energy Independent Terms

The value of the geometry term, SANGLE, in Equation 3.9 depends upon the size of the lead collimator being used, and upon the sample to detector distance. Section 2.4.2, Table 2.3 lists the geometry factors used for the data recorded in the 4TH1 gamma spectrometer.

The FLUXT term of Equation 3.9 represents the total number of captures experienced by the sample divided by 100. It is given by:

$$\text{FLUXT} = \frac{F_2 N \sigma_c F_1 \phi t}{100} \qquad (3.10)$$

Where the terms are the same as those described for Equation 3.8.

Each of the five numerator terms of Equation 3.0 are determined for each spectrum run. F_2N is the total number of sample atoms seen by the detector using the 1 inch collimator. σ_c is the average thermal neutron capture cross section for the sample. Usually σ_c is taken as the cross section for 2200 m/sec neutron capture. This

corresponds to assuming the sample is a 1/v absorber. For non-1/v absorbers, the effective capture cross section as defined by Westcott (W-1) is used. Section 2.2.2, Equation 2.1 indicates the equation used, and empirical values needed to perform the Westcott calculation.

The $F_1 \phi$ t term of Equation 3.0 is the total average time integrated thermal neutron flux seen by the sample. F_1 is the correction in the flux depression in the sample. Flux depression in the sample is approximated to about 3 % using a method proposed by Nisle (N-1) and used by Orphan (O-1).

F_1 is calculated by:

$$F_1 = \exp (- N\sigma_c \bar{x}) \quad , \quad (3.11)$$

where: $N\sigma_c$ is the macroscopic absorption cross section of the sample viewed, in cm^{-1}; $\bar{x}$ is equal to the average distance in cm that a neutron travels in the sample. $\bar{x}$ is approximated as being one half of the average thickness of the sample in the direction of the incoming neutron beam.

Section 2.2.2 describes the measurement of the thermal neutron flux in the 4TH1 facility. For most runs, the measured value of 1.8×10^8 $n/cm^2 sec$ was used for the thermal flux term of Equation 3.10. This value is assumed accurate to $\pm$ 10% relative standard deviation.

Provision was made so that it is possible to monitor the flux during a run by placing gold foils on the aluminum

sample holder, out of the Ge(Li) detector's line of sight. Relating the counting rate of these foils to the counting rates of foils irradiated in a known flux also gives an estimate of the thermal neutron flux incident upon the sample. More than one foil can be used on the holder to monitor the divergence of the neutron beam about the sample. Such a monitoring system was used in a few cases to check the uniformity of the flux in the beam port. The results showed that the flux was constant to ± 1.5 inches off the center line of the 4TH1 beam port. Thereafter it dropped to 95% of its centerline value at 2.0 inches off the centerline position.

The time t of the run was the actual running time of the run in seconds minus any correction for dead time in the analyser, or associated electronics. For the triple coincidence operation the dead time correction to the analyser was negligible, as is evident from the counting rate data given in Section 2.4.1, Table 2.2. Some cases of Compton suppression operation had dead time corrections of up to 20% depending upon the counting rate being observed in the run.

3.4.2 Energy Dependent Terms

The EFF term of Equation 3.6 represents the contribution of the gamma energy dependent terms to the intensity calculation. EFF is computed by using an array EFFCY(J)

that stores the energy dependent terms for the J-th energy value. The EFFCY(J) array values are determined by using the measured data on system efficiency, self-absorption, in the sample, and attenuation of the gamma beam.

Depending upon whether Compton suppression or triple coincidence data is being analysed, the efficiency curves of either Sections 2.4.6, or 2.4.5 are used. The self-absorption in the sample, and the attenuation of the gamma beam terms are calculated using the method outlined in Section 2.4.4.

In general the accuracy of the efficieny values was assumed to be $\pm 10\%$ relative standard deviation, and the attenuation and self-absorption correction terms were assumed to be accurate to $\pm 2\%$.

The EFFCY(J) array was determined for energy points 200 keV apart in energy for Compton suppression data, and for points 500 keV apart in energy for triple coincidence data. The EFF value of the energy dependent terms at other gamma energies was calculated using second order interpolation on the values of the EFFCY(J) array using three values of tabulated energy that were the closest to the desired energy value. This value of EFF was then used in Equation 3.6 for the intensity calculation of a gamma peak of energy E.

3.5 Fractions of Emitted Energy Observed

After calculating the energies and intensities of the well resolved lines of a sample, one is able to check if the gamma rays so listed do account for the excitation energy of the product nucleus. For a sample composed of one isotope (Z,A) a thermal neutron capture excites the product nucleus by BE_j, the neutron binding energy of the (Z,A+1) nucleus. Thus for 100 captures in an isotope, one should have the identity:

$$100 \times BE_j = \sum_I I(I) \times E(I) \quad , (3.12)$$

where: I(I) is the intensity in number of capture gamma rays of energy E(I) emitted per 100 captures in the isotope; E(I) is the energy of the I-th gamma ray emitted by the product nucleus in keV; and the summation I is taken over all the capture gamma lines of the product nucleus.

Equation 3.12 is a true identity when the summation does indeed account for all of the capture lines characteristic of the isotope, and when the intensity values, I(I), have been determined correctly.

In the cases where a sample is composed of more than one isotope, each capture produces on the average an excitation energy in the sample of:

$$\overline{BE} = \frac{\sum_{j=1}^{J} N_j \sigma_j \cdot BE_j}{\sum_{j=1}^{J} N_j \sigma_j} \quad , \qquad (3.13)$$

where: both summations are taken over all of the J isotopes which compose the sample; $\overline{BE}$ is the "average neutron binding energy" of the sample consisting of J isotopes; BE_j is the neutron binding energy of the j-th product nucleus; $N_j \sigma_j$ is the effective macroscopic capture cross section for the j-th isotope; the lower summation gives the total macroscopic capture cross section for the sample.

Equation 3.13 shows that the neutron binding energy of the j-th product nucleus is weighted by the fraction of captures that the j-th isotope contributes to the total number of captures in the sample.

Using Equation 3.13 as the definition of the average binding energy for the sample, one obtains an equation that is equivalent to Equation 3.12 for the case when the sample consists of more than one isotope. This is:

$$100 \times \overline{BE} = \sum_{I} I(I) \times E(I) \quad , \qquad (3.14)$$

where: the summation is taken over all of the capture lines characteristic of the sample; the intensity value I(I) is the number of gamma rays of energy E(I) emitted per 100

captures in the sample.

It is usually more convenient to work with the fraction of observed gamma rays seen, F, which is defined, using Equation 3.14 as:

$$F = \sum_{I} \frac{I(I) \times E(I)}{\overline{BE}} \quad , \qquad (3.15)$$

where F represents the percent fraction of observed gamma rays seen, and the other terms are as previously defined.

Appendix E gives as error estimate on the F value as calculated by Equation 3.15. Using an estimated percent relative standard deviation of ±15% for the intensity uncertainty for strong lines, Appendix E estimates that F will have a percent relative standard deviation also of ±15%.

Since F is the percentage of gamma rays observed, F will be close to 100% in the cases when all of the observed gamma rays are well resolved. When there is a large unresolved continuum portion in the spectrum, F is expected to be significantly less than 100%.

In such cases it is desirable to perform an analysis upon the amount of capture gamma energy that is in the continuum portion of the spectrum, and to determine this amount as a function of gamma energy. To accomplish this the continuum due to the unresolved capture gamma peaks

is broken into a number of small energy bins, and the intensity per bin determined. If one denotes the average bin energy by $\overline{E}(K)$, and the intensity in this bin as I(K), a new value of the fraction of observed gammas, F, using Equation 3.15 can be written as:

$$F = \sum_{I} \frac{E(I) \times I(I)}{\overline{BE}} + \sum_{K} \frac{\overline{E}(K) \times I(K)}{\overline{BE}} \quad , \qquad (3.16)$$

where the second summation is taken over all of the energy bins used in the continuum analysis, and thus F includes the effects of the unresolved capture gamma rays in the continuum of the spectrum.

3.6 Continuum Analysis

Many of the spectra studied with the pair spectrometer show evidence of having a large continuum region due to unresolved gamma lines. This has been mentioned in Chapter 1 and examples are given in Chapters 5-9. The Compton suppression data also shows this unresolved region, but it is generally obscurred by the large background continuum in these spectra due to other causes. The purpose of this analysis of the continuum portion of the spectrum is to account for the energy intensity that is contained in this region due to unresolved capture gamma lines.

The continuum in the pair spectrometer data is assumed to come from four main sources:

1. The counts due to the unresolved low intensity capture gamma lines.
2. The counts due to background.
3. The counts due to resolved peaks at higher energies.
4. The counts due to weak unresolved peaks at higher energies (higher energy continuum effect).

The first contribution to the continuum is the effect that is being studied. The other three contributions are considered in the next three sections. Computer code GAMABC which was written to perform the analysis of the continuum is described in Section 3.6.4.

3.6.1 Continuum from Background Gamma Rays

The counts due to background gamma rays scattered from the shielding material of the spectrometer and from the sample, contribute to the general continuum portion of the spectrum. The magnitude of this effect is determined by studying a background run forthe pair spectrometer in which no sample is placed in the sample holder. Such a run gives an indication of the well resolved background lines as well as the background continuum due to shielding scattered gammas. The results of such a background run are presented in Chapter 4.

The background will vary somewhat from sample to sample. This is due in part by varying amounts of neutron

scattering taking place in the samples. The scattered neutrons determine the intensity of the resolved capture gamma rays seen by the Ge(Li) detector which are characteristic of the shielding materials, as well as the background continuum observed from scattered gamma rays in the shielding material. Thus the magnitudes of the resolved capture peaks due to captures in the shielding material are an indication of the amount of neutron scattering taking place in the sample.

The intensity of the background counts in the continuum of a particular data run is estimated by normalizing the pure background run to either the same time as the data run, or to the magnitudes of the resolved background capture peaks in the data run. The continuum due to this normalized background run is then calculated and subtracted from the continuum of the sample run, after aligning the two runs with respect to gamma energy. Section 3.6.4 describes how this subtraction is done in the GAMABC code.

3.6.2 Resolved Peak Response Function

A major part of the continuum is due to low energy counts which arise from higher energy resolved gamma peaks in the spectrum. Such low energy continuum counts are due to incomplete absorption of the gamma energy in the Ge(Li) detector. The shape and magnitude of the continuum, which is a function of the particular Ge(Li) detector being used to study a monoenergetic gamma ray of energy E, is designated

as the detector peak response function at energy E. Thus in analysing the continuum it is necessary to determine the shape and magnitude of this peak response function, and to determine its variation with gamma peak energy. The determination is done empirically by studying the spectra in which a strong peak is observed, and where the low energy continuum associated with the strong peak can be seen. Since usually only a few such cases are available, the energy dependence of the peak response function is inferred by using only a few points and by assuming a linear variation between the peak energy and the observed shapes and magnitudes of the peak response function.

Figure 3.3 illustrates the general shape of the variation of the peak response function versus channel number (energy) found suitable for the pair spectrometer used in this work. The magnitude of the continuum is directly related to the area under the peak by the constants shown in Figure 3.3. The variation of these constants with different gamma peak energies is determined empirically from spectra having the desired characteristics listed above.

Figure 3.3 shows that there are essentially five regions which make up the peak response function, and these can be grouped into two main areas. The first is the pedestal upon which the peak is situated, and is composed

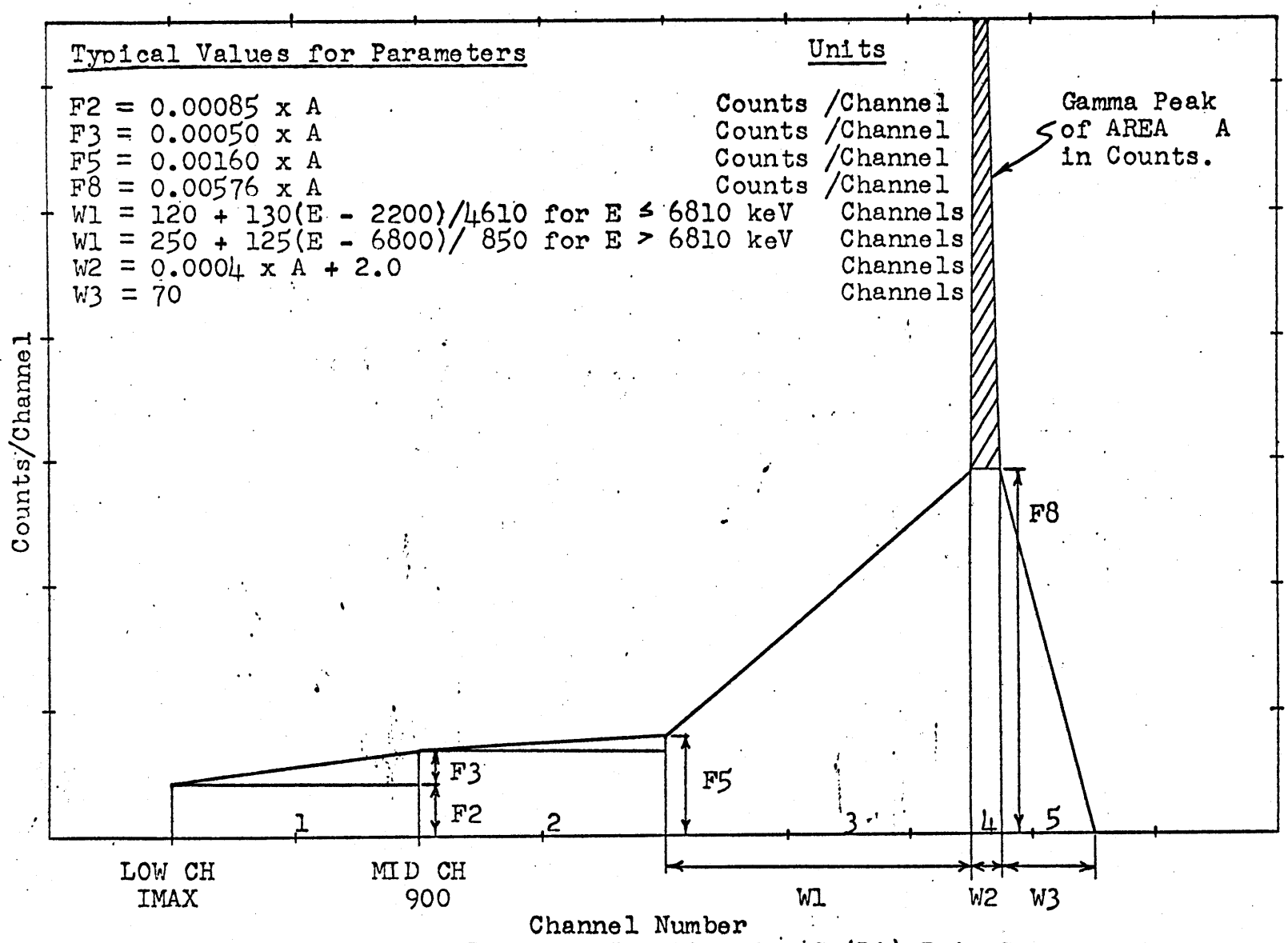

Figure 3.3 Shape of Peak Response Function for Ge(Li) Pair Spectrometer.

of regions 3,4, and 5 in Figure 3.3. This pedestal is caused in part by the timing and window width settings of the pair spectrometer and in part by bremsstrahlung losses which affect the low energy side of the peak. It is also found that the collimator size will affect the response of the system due to the fact that the position of the impinging gamma beam upon the active region of the Ge(Li) detector changes somewhat when different collimators are used. The larger size collimator produces a more pronounced pedestal under the peak.

Region 1 and 2 of Figure 3.3 compose the second area of the peak response function. They can be referred to as the long low continuum that the peak contributes to the spectrum at 500 keV and more below the peak energy.

The peak response function as shown in Figure 3.3 is described completely by specifying 9 parameters. Typical values for these parameters are given in the tables listing the GAMABC parameters in Chapters 4 through 9 in which the results of data analysis are presented. To determine suitable values for these parameters it was necessary to study spectra with isolated peaks for which the response could be determined. Table 3.1 illustrates the results of such a study. Figures 3.4 to 3.6 indicate the type of spectral data studied to obtain the results of Table 3.1. Each of these Figures show a perturbation of the spectrum

Table 3.1 Peak Response Function Parameters for Ge(Li) Pair Spectrometer Data at Various Gamma Peak Energies

Sample	H	Be	Fe	Fe
Run No	488	11141	11071	11071
Facility	9CH2	4TH1	4TH1	4TH1
Collimator Size (in inches)	5/8	1	1/2	1/2
Energy of Line Studied (keV)	2223	6810	5920-6018	7631-7645
Peak Area in Counts x 10^3	99.2	12.6	37.5	57.6
Parameter: (a)				
F2 (b)	0.0022	0.0012	0.00085	0.00085
F3 (b)	-	0.0007	0.00050	0.00050
F5 (b)	0.0022	0.0022	0.00160	0.00160
F8 (b)	0.0065	0.0065	0.00576	0.00576
LOW CH	IMAX	IMAX	IMAX	IMAX
MID CH	IMAX	900	900	900
W1 (c)	120	250	230	375
W2 (c)	40	5	15	25
W3 (c)	70	70	70	70

(a) As designated by the notation of Figure 3.3.

(b) F factors given in units of peak area A.

(c) W factors given in units of channels.

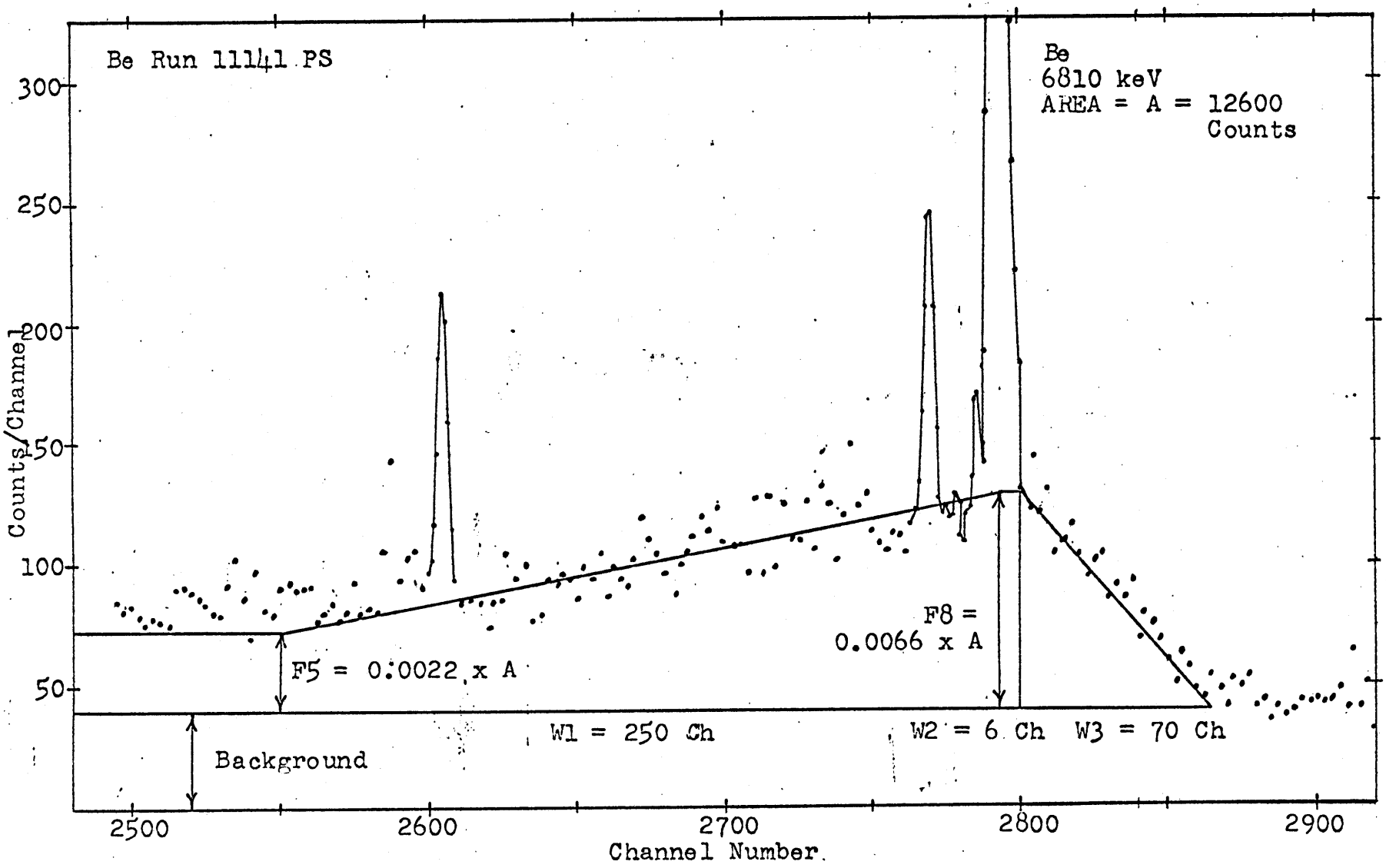

Figure 3.4 Ge(Li) Pair Spectrometer Response to Be 6810 keV Peak.

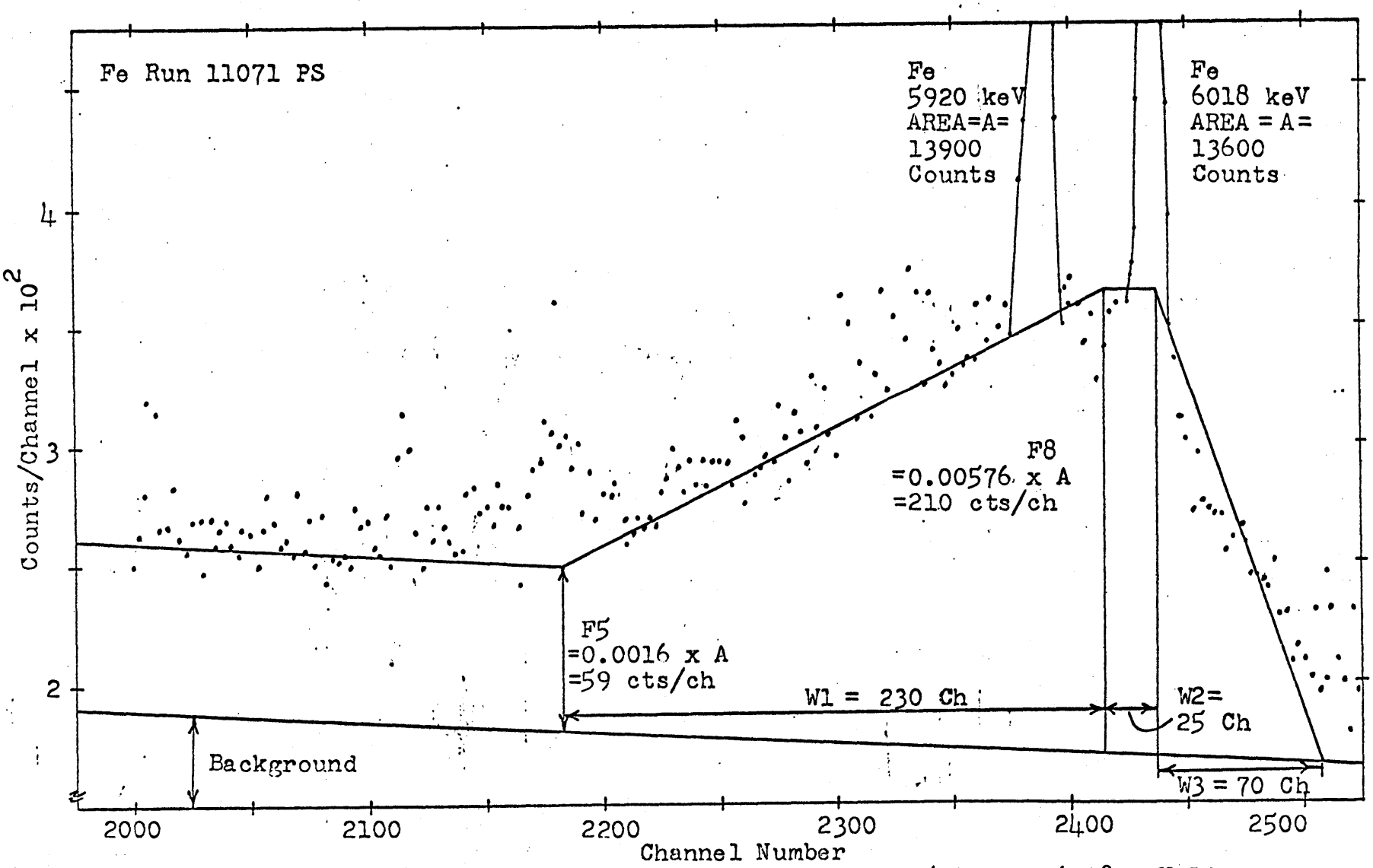

Figure 3.5 Ge(Li) Pair Spectrometer Response to Fe 5920 and 6018 keV Lines.

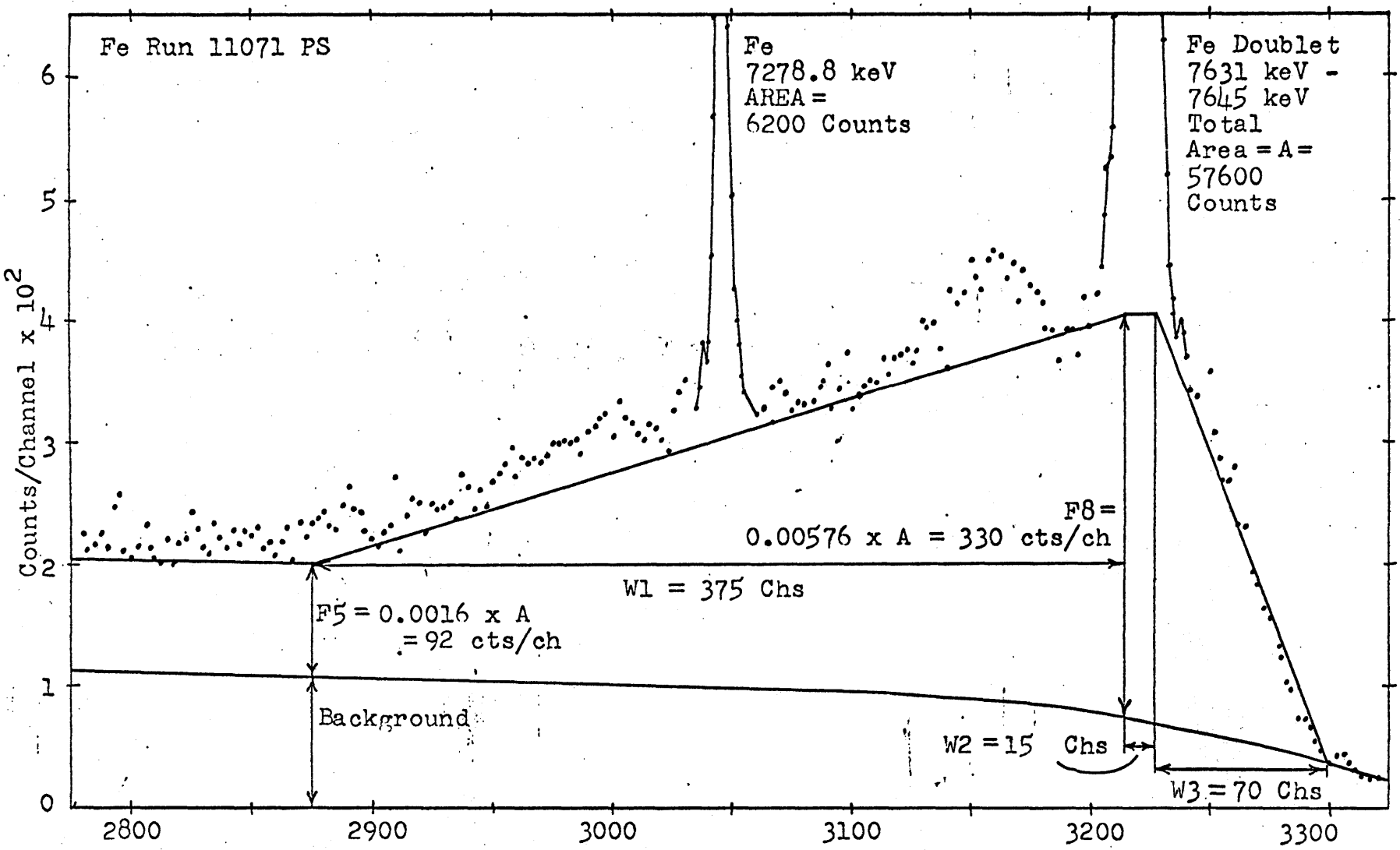

Figure 3.6 Ge(Li) Pair Spectrometer Response to Fe 7631-7645 keV Doublet.

about a large peak, and they also indicate somewhat the low energy continuum that is characteristic of the data.

From Table 3.1 and the Figures 3.4 - 3.6 it is inferred that the factor W1 is energy dependent, that W2 depends upon the area of the peak and that the other parameters are to a first approximation not dependent upon the energy of the gamma peak causing the response. The factor W1 is fit linearly to the peak energy causing the response by:

$$W1 = 120 + 130(E-2200)/4610 \text{ for } E_\gamma \leq 6810 \text{ keV}$$

and

$$W1 = 250 + 125(E-6800)/850 \text{ for } E_\gamma \geq 6810 \text{ keV} \qquad (3.16)$$

The W2 channel width is given by:

$$W2 = 0.0004 * \text{Peak Area} + 2.0 \qquad (3.17)$$

It is evident from the figures shown that in order to determine the shape and magnitude of the peak response function, long runs and good statistics are required. The fact that in the pair spectrometer the background is low is advantageous from the standpoint of being able to analyse the continuum for the unresolved gammas but by the same token this makes it difficult to determine the magnitude of the parameters which determine the peak response. A high degree of accuracy is required because small changes in the response can greatly change the results of the analysis.

This is because the peak response per channel number is summed over all of the channels below the peak causing the response.

Table 3.2 shows the percent of counts recorded that were analysed as being in the well resolved gamma peaks for the cases of iron and beryllium.

Table 3.2

Percent of Total Counts that are in the Well Resolved Peaks for Iron and Beryllium

Run Number	Fe 11071	Be 11141
Total Counts in Spectrum	1089239	425883
Counts in Background	947265	387576
Counts in well resolved peaks	162887	55818
Percent of total counts in well resolved peaks	15%	13%

NOTE: The summations are taken from the lower channel number limit, IMAX, to channel number 4095.

The data of Table 3.2 show that about 85% of the counts recorded in a spectrum are classified as being background data. Since the data of Table 3.2 are for cases where the continuum due to any unresolved gamma rays is small, the recorded background counts must be either counts caused by the response of the system to higher energy gamma rays or counts caused by actual background gamma rays scattered

from the shielding material of the spectrometer. The fact that these effects make up about 85% of the recorded events indicate the problem involved in subtracting these effects.

Appendix F discusses the sensitivity of the GAMABC analysis of the continuum with reference to the determination of the peak response function parameters.

There are two references available which discuss the peak response of Ge(Li) detectors in some detail. Huang (H-7) has studied the response in the free mode operation and normalizes the line shapes obtained with different energy gamma rays to the full energy peak area. Basically shape of the response is as shown here for the high energy gamma rays (6 to 10MeV) with the addition of the full energy and single escape energy peaks to the response. Allen (A-2) has considered the pair spectrometer case as well as the free mode case. He normalizes the response function to the low continuum plateau for the various peaks. The same shape responses are obtained in this experiment except for a high energy (17.64 MeV) peak response where the double escape peak is quite weak and the continuum is large and increases as the energy decreases. Neither Huang nor Allen have reported analysing the continuum portion of the spectrum by using the peak response function. However, Huang performs a least squares fit of peak response functions to the resolved peaks in the

free mode spectrum and from the fit so obtained can determine the intensity of the gamma line being studied. For analysing the unresolved gamma continuum such a method would not be suitable unless major modifications were made in the spectrum energy range over which the least squares fit would apply.

3.6.3 Unresolved Peak Response Function

A response function for the unresolved gamma peak continuum is also needed. It is assumed that this response function, denoted as the bin response, will have the same shape as the one for the well resolved peaks. Figure 3.7 shows the shape of the bin response function used versus channel number (energy). The bin area in counts is the total area under the bin. This area is divided by a reduction factor, RED, to give an area which is corrected for the pedestal effect of the bin and more correctly approximates the bin area due to the unresolved gamma rays. The RED factor depends upon the F8 parameter of the response function used.

The bin width used in the bin response function has a width approximately equal to that of the base width of the peaks in the spectrum. This is usually 10 to 20 channels, or 2 to 4 times the full width at half maximum of the resolved peaks. This width is chosen so as to enable essentially the same shape and magnitude response function to be used

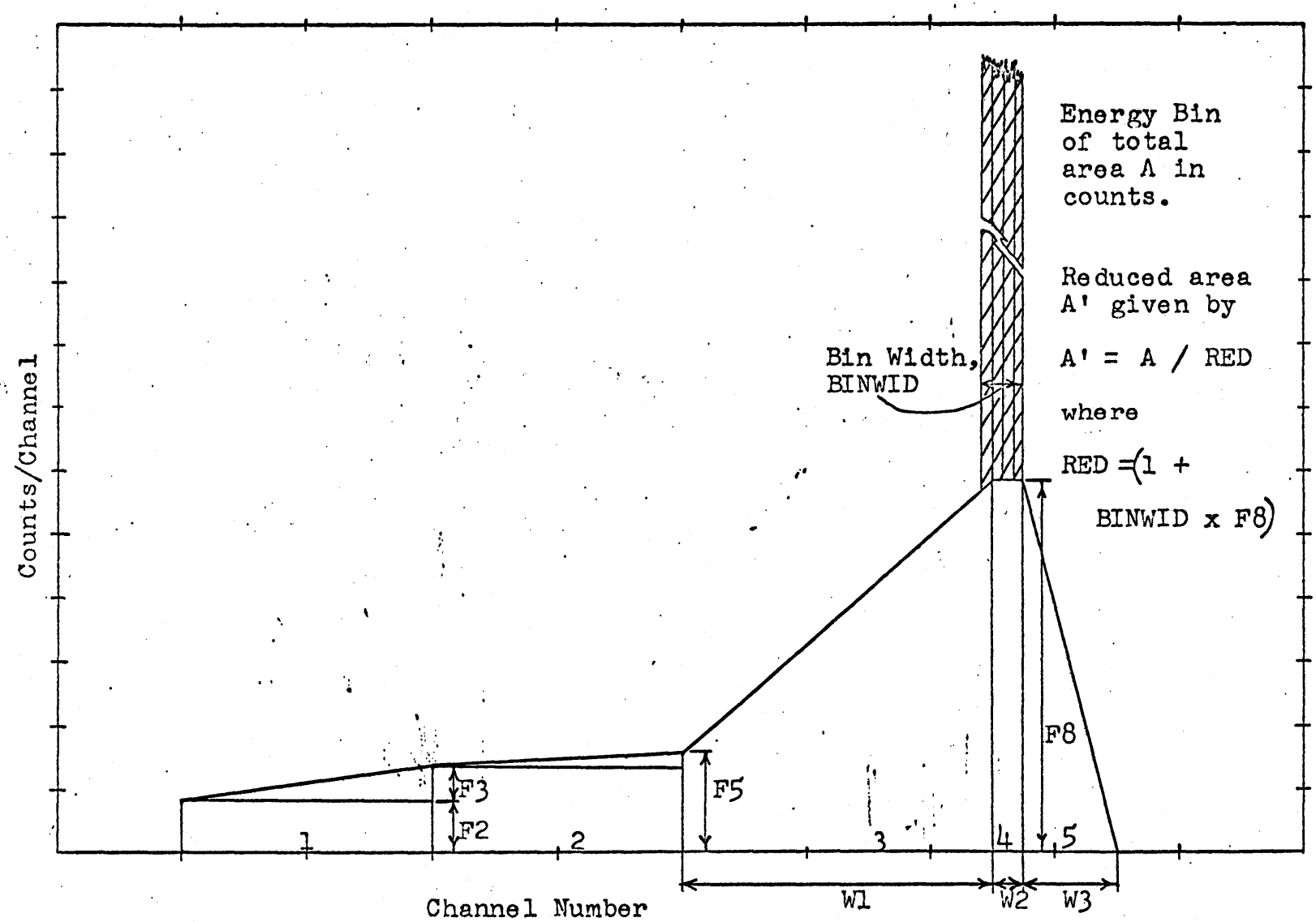

Figure 3.7 Response Function for Unresolved Gamma Continuum.

for the bin response as is used for the resolved peak response function.

3.6.4 GAMABC Code for Unresolved Region

To carry out the operations described in the previous sections, computer code GAMABC was written . Figure 3.8 shows a flow diagram of the major sections of GAMABC. The first step of the analysis consists of studying the well resolved gamma peaks of the spectrum. Computer code GAMANL (H-1) is used to do this. Upon completion of this analysis, the code stores the peak parameters, and also stores the continuum of the data. This continuum is defined as the smoothed spectrum minus the resolved peaks that were analysed in subroutine PKANAL of GAMANL.

The next step involves reading in the background data, calibration lines, and the main background peaks that appear in the spectrum. The background data is data recorded without any sample and provides an estimate of the shielding background present in the spectrum as discussed in Section 3.6.1. Subroutine BFAC calculates the factor relating the background in the spectrum to the background measured without a sample. BFAC can be bypassed and a background normalization factor read in.

The well resolved peak energy values are searched to determine which are the strong background lines, and

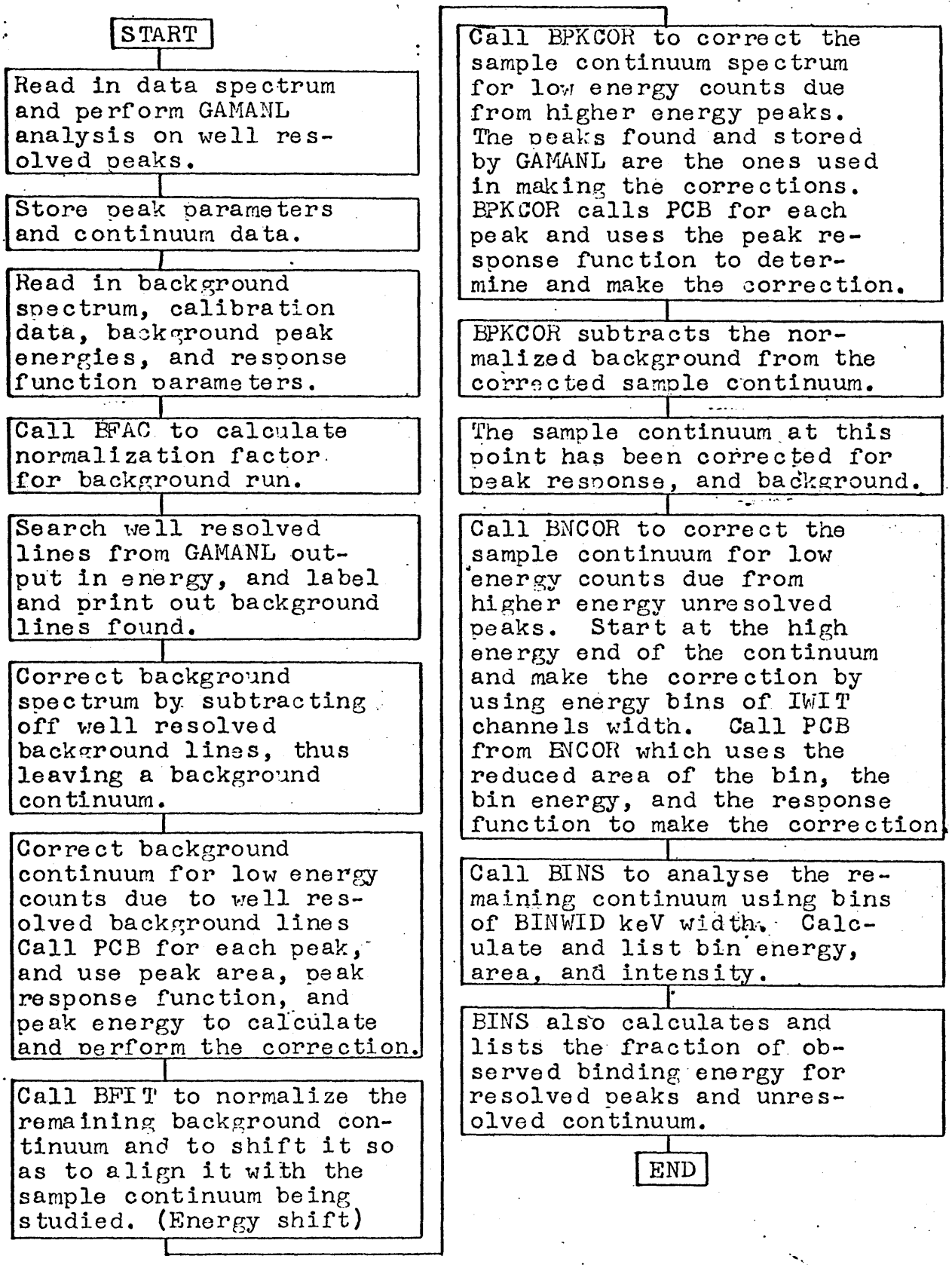

Figure 3.8 Flow Diagram Showing Major Sections of GAMABC Computer Program.

which are lines characteristic of the sample. The background lines are so noted in the output. These lines are given in Table 4.6, Section 4.2.2.

The background spectrum is corrected (1) for the strong background lines, and (2) for the continuum due to the strong background lines. Subroutine PCB performs this peak response correction for each of the background peaks.

Subroutine BFIT aligns the background data continuum to the sample data continuum with respect to gamma energy. To do this two energy calibration peaks are used, as well as the keV/channel for each run.

Subroutine BPKCOR corrects the continuum data for the continuum counts due to resolved high energy peaks. Each peak determined by GAMANL influences the continuum by its particular peak response function. Subroutine PCB, called by BPKCOR, used the peak response function to correct the continuum for each peak in the spectrum. BPKCOR also subtracts the background continuum from the continuum data using either the calculated normalization factor or the value read in.

Thus at this point in the code the continuum has been corrected for: (1) the counts due to the shielding background, and (2) the low energy counts due to the resolved higher energy peaks. The remaining continuum then should be composed of only the counts due to the unresolved gamma

rays. However as mentioned in Section 3.6.3 there is a continuum of low energy counts caused by the detector response to higher energy unresolved gamma rays, which must be determined and subtracted off.

Subroutine BNCOR is called to make this last correction. The correction is made by sweeping through the continuum from the high energy side. A bin width, two or three times the average FWHM of the well resolved peaks in the spectrum, is used. The same width is used for all the bins from the high energy region to the low energy region.

BNCOR starts at the highest energy at which the continuum has counts, and uses a bin width which has been read as an input parameter. The number of counts within the bin is calculated (bin area), this area is reduced by the factor RED as explained in Section 3.6.3. Subroutine PCB, called BNCOR, uses the reduced bin area, the average bin energy, and the peak response function parameters to determine the peak response function for the bin. All of the channels affected by this response function for the bin are then corrected by subtracting the bin response function correction as determined by PCB. After the highest energy bin has been corrected for, the next lower energy bin is studied, (with the bin area calculated, PCB called and corrections made as described above). The process

repeats itself until the lower limit of the data at channel number IMAX is reached. In this way all of the lower energy continuum is corrected for the perturbations due to the higher energy continuum. Upon leaving BNCOR the remaining continuum represents only the counts due to the unresolved gamma lines.

The last subroutine called is BINS which performs the intensity analysis upon the remaining continuum. BINS calculates the bin area in counts using a bin width in energy that is an input parameter. Usually this bin width is 250 keV. The bin area in counts is converted to intensity using an efficienty value at an average bin energy, SANGLE, and FLUXT, as described in Sections 3.4.1 and 3.4.2. BINS also calculates the percent fraction of observed gamma rays seen in the sample both for the resolved gamma lines, and for the unresolved continuum.

Appendix F discusses the sensitivity of the GAMABC analysis of the continuum. Appendix H gives the Fortran IV listing for the GAMABC code.

4. BACKGROUND, IRON AND BERYLLIUM RESULTS

4.1 Presentation of Results

In presenting the results of analysis in this chapter and in succeeding chapters, a uniform procedure has been followed. Each sample was studied with two spectrometer data runs: (1) Compton suppression operation for the gamma energy range from 200 keV to 3.5 MeV, and (2) pair spectrometer operation for the gamma energy range from 1.5 MeV to 9.5 MeV. The physical properties of the sample parameters and spectra for each of the runs are presented.

The Compton suppression data are analysed by using computer code GAMANL. The GAMANL parameters used, and results obtained for gamma energies and intensities are presented in two tables.

The pair spectrometer data are analysed by computer code GAMABC which uses GAMANL internally. The parameters used for GAMABC and GAMANL in this data are presented. The GAMANL results are presented in tabular form similar in form to the GAMANL results obtained for Compton suppression data. The GAMABC results of the continuum analysis are given in tabular form, with the percentoof sample binding energy seen in the data calculated. The energy and intensity of each bin in the continuum are given.

A discussion of the results obtained from the continuum analysis is given with regard to the observed fraction of average binding energy. A final section is devoted to comparing the results of the intensities of the well resolved peaks with published results.

Appendix G discusses the formats and composition for each of the three computer output tables: (1) GAMANL parameters for Compton suppression data, or GAMANL and GAMABC parameters for pair spectrometer data, (2) GAMANL results, and (3) GAMABC results.

It is noted that the intensity values used in the intensity comparison tables and the GAMABC results tables are those values obtained using the peak area as calculated by the summation method. This is done in order to be consistent in presenting the results. Both intensity values, as determined using the summation method and the Gaussian method, are given in the GAMANL results tables. A comparison between these two methods of area calculation can therefore be made. The agreement between the two methods is usually quite good. Appendix C discusses the use of these two methods of area calculation in greater detail.

4.2 Background Results

Background runs were performed for both the Compton suppression and the pair spectrometer modes of operation. These runs were necessary in order to determine the magnitude of the continuum due to the background from shielding materials in the pair spectrometer case, and to determine the energies of the background peaks. Table 4.1 gives the run information for these background runs. An empty sample holder was used for each run. It is to be noted that the FLUXT term and associated intensity calculation is meaningless for these runs since no sample was being studied. However the FLUXT value used in the calculation corresponds to an equivalent 1.2 grams of iron at the sample position in the 4TH1 facility. This was used as an estimate for the amount of iron seen by the spectrometer as background during these runs.

4.2.1 Background Compton Suppression Results

Figure 4.1 shows the background Compton suppression spectrum for run number 11263 of 135 minutes duration. Tables 4.2 and 4.3 present the GAMANL parameters and GAMANL results for this run. It is noted that the main background peaks seen in this energy range are: the annihilation peak at 511 keV, and the argon-41 gamma decay peak at 1293 keV. The hydrogen capture peak at 2223.3 keV is also visible; its intensity increases if the sample

being studied is contained in a poly vial as was the case for many of the samples studied.

The weak peaks that are listed in Table 4.3 are not deemed to be significant peaks since their measured full width at half maximum is less than expected and their counting statistics are poor. This fact is also shown by re-analysing the data of the background run 11263 with the peak height criterion (BGER) raised to 3.0 instead of 2.0. Table 4.4 gives the GAMANL output for this case. It is seen that only the three strongest peaks of Table 4.3 appear, the other weaker peaks having been rejected by the stronger peak height criterion.

TABLE 4.1 BACKGROUND SAMPLE DATA AND RUN INFORMATION

Sample: Background At. Wt.: -

Wt: - Description: Sample Holder

Holder: Al Only, No Vial

Isotope:

Natural %:

Thermal Capture :

Percent Captures in Natural Mixture:

Binding Energy of Product Nucleus:

Effective Capture Cross Section: -

Westcott Correction: -

Average Binding Energy for Sample: -

Flux Depression Factor: $F_1 = 1.00$ $N_T\sigma_c = 0.03 * cm^2 \rho\bar{x} =$ -

* for 1.2 gm Fe at Sample Position

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	11263	11271
Computer Job No:	J51084	J90666
Average Thermal Flux: ϕ (n/cm^{2}sec)	1.83×10^8	1.83×10^8
Fraction of Sample Viewed by 1" Collimator: F_2	1.00	1.00
Collimator Used: Diam.	1/2"	1/2"
Duration of Run (Min):	135	1106.1
Dead Time Corrected Run Time: (Min) t	134	1106.1
SANGLE	1.58×10^{-5}	1.58×10^{-3}
FLUXT = $F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	4.20×10^8	4.10×10^9

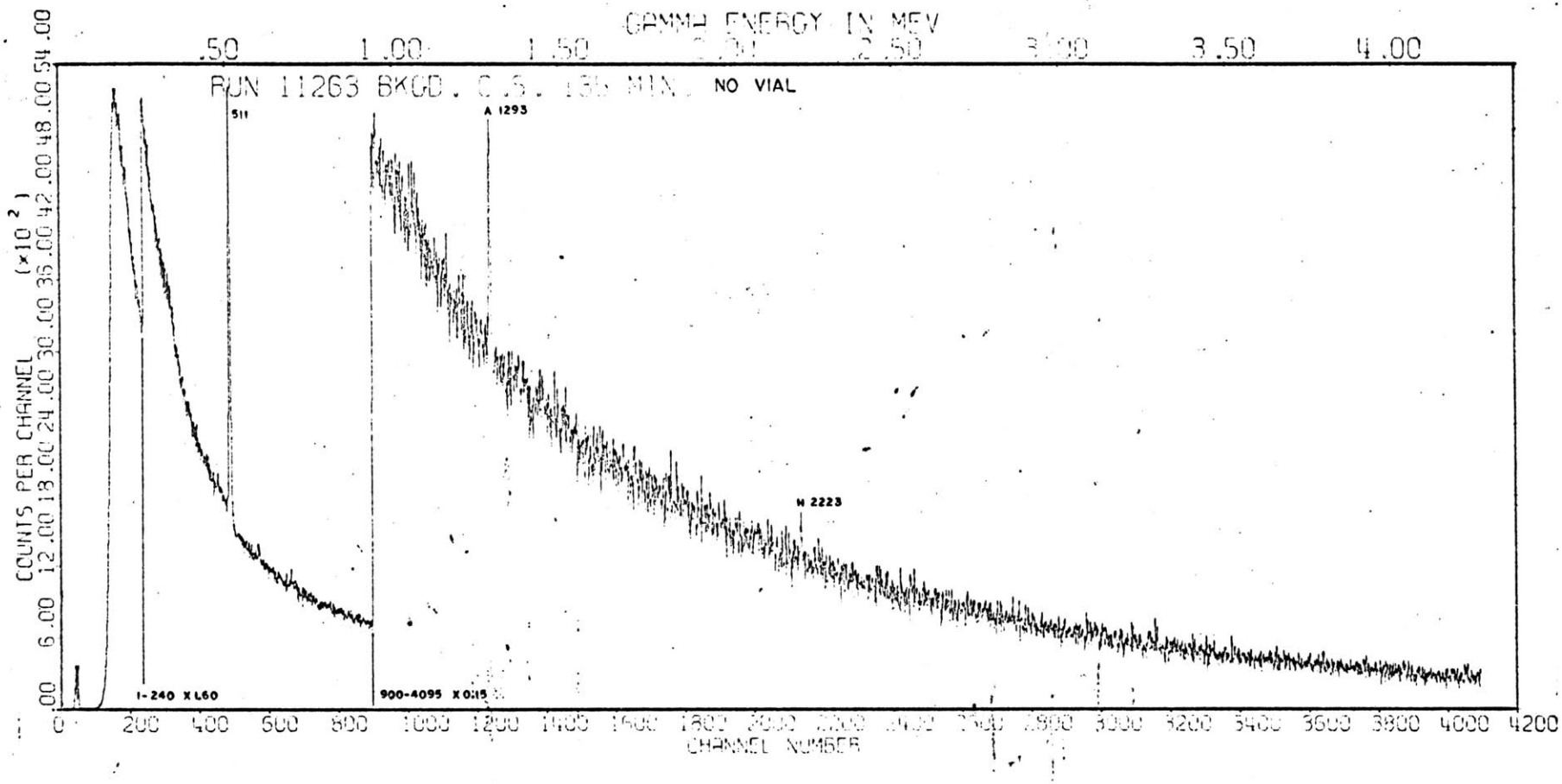

Figure 4.1 Background Compton Suppression Spectrum 11263

```
PARAMETERS AND INPUT DATA FOR RUN 11263  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  184
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   2.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  6.00 FWHM RANGE ERFW =  2.50
ENERGY PER CHANNEL NUMBER (KEV) = 1.039
CALIB1 E = 511.0 CNTR =  490 CORR = 488.0 FWHM =  5.65
CALIB2 E =1293.6 CNTR = 1241 CORR =1241.0 FWHM =  5.40
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.420E 09
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.572E-01 0.308E-01 0.205E-01 0.158E-01 0.128E-01
 0.117E-01 0.970E-02 0.835E-02 0.723E-02 0.651E-02
 0.571E-02 0.502E-02 0.445E-02 0.396E-02 0.352E-02
 0.297E-02 0.270E-02 0.246E-02 0.203E-02 0.186E-02
 0.164E-02 0.143E-02 0.122E-02 0.108E-02 0.999E-03
 0.888E-03 0.778E-03 0.706E-03
NUMBER OF PEAKS ANALYSED = 11    J51084
```

Table 4.2 Background Compton Suppression Run 11263 GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1	195.9	192.7	272.1	0.0392	2013.5	20.1	5.223	5.09	0.58E-01	15.	S *
					1607.4	24.6	4.170	5.66			
2	316.0	304.9	140.0	0.0395	419.5	33.1	1.578	3.11	0.40E-01	6.	S *
					823.5	31.4	3.098	5.63			
3	324.6	313.0	128.8	0.0374	502.9	30.6	1.944	4.14	0.39E-01	7.	S *
					757.4	33.5	2.928	5.63			
4	332.1	320.0	137.7	0.0410	416.4	32.5	1.648	3.14	0.38E-01	6.	S *
					809.3	31.1	3.203	5.63			
5Ann	511.0	489.5	3609.5	2.2403	21433.1	1.6	131.996	5.65	0.24E-01	25.	S *
					21032.6	1.9	129.529	5.58			
6	751.8	720.0	73.1	0.0801	208.3	34.1	1.865	2.97	0.17E-01	6.	S *
					420.1	31.5	3.762	5.50			
7	952.1	912.4	69.8	0.1030	244.4	28.3	2.751	3.69	0.13E-01	7.	S *
					395.3	29.4	4.449	5.43			
8	1034.0	991.4	61.7	0.0994	225.7	29.3	2.675	3.85	0.13E-01	7.	S *
					347.2	31.8	4.114	5.39			
9Ar	1293.6	1240.7	287.3	0.6341	1684.4	7.5	23.685	5.40	0.11E-01	18.	S *
					1580.4	11.6	22.222	5.27			
10H	2223.2	2136.2	45.4	0.2334	217.4	22.9	5.807	4.97	0.56E-02	10.	S *
					221.4	124.5	5.912	4.67			

Table 4.3 Background Compton Suppression Run 11263 GAMANL Results

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1	195.9	192.7	272.0	0.0392	2011.4	20.1	6.257	5.09	0.48E-01	15.	S *
					1457.4	22.5	4.533	5.09			
2 An	511.0	489.5	3609.2	2.2400	21430.2	1.6	158.468	5.65	0.20E-01	25.	S *
					21476.8	1.8	158.813	5.65			
3 A	1293.6	1240.7	287.4	0.6341	1682.9	7.5	28.382	5.40	0.89E-02	18.	S *
					1635.5	7.9	27.582	5.40			

Table 4.4 Background Compton Suppression Run 11263 GAMANL Results
(BGER = 3.0)

4.2.2 Background Pair Spectrometer Results

A background spectrum obtained with the pair spectrometer is shown in Figure 4.2, run 11271. From the spectrum it is seen that small amounts of iron, hydrogen, and cadmium are present in the background data, as well as a small continuum of scattered gammas from the shielding material.

Table 4.5 gives the GAMANL input parameters for this run, while Table 4.6 gives the GAMANL results. The code GAMABC was not used on this pair spectrometer data because it was background data and analysis of the continuum was not needed.

Table 4.6 indicates the principle resolved gamma lines that are in the pair spectrometer background for the 4TH1 facility. Iron lines predominate in intensity, and it is estimated from this data that an equivalent 0.5 to 1.3 grams of iron were seen. This assumes the iron to be concentrated at the sample holder position, which of course it is not. Most of the iron contribution is felt to come from the Atomium gamma shield surrounding the Ge(Li) detector, and from the iron in the heavy density concrete shielding material of the facility. Also observed are small amounts of hydrogen and cadmium which are present in the shielding material. A total of 13 peaks are listed as background.

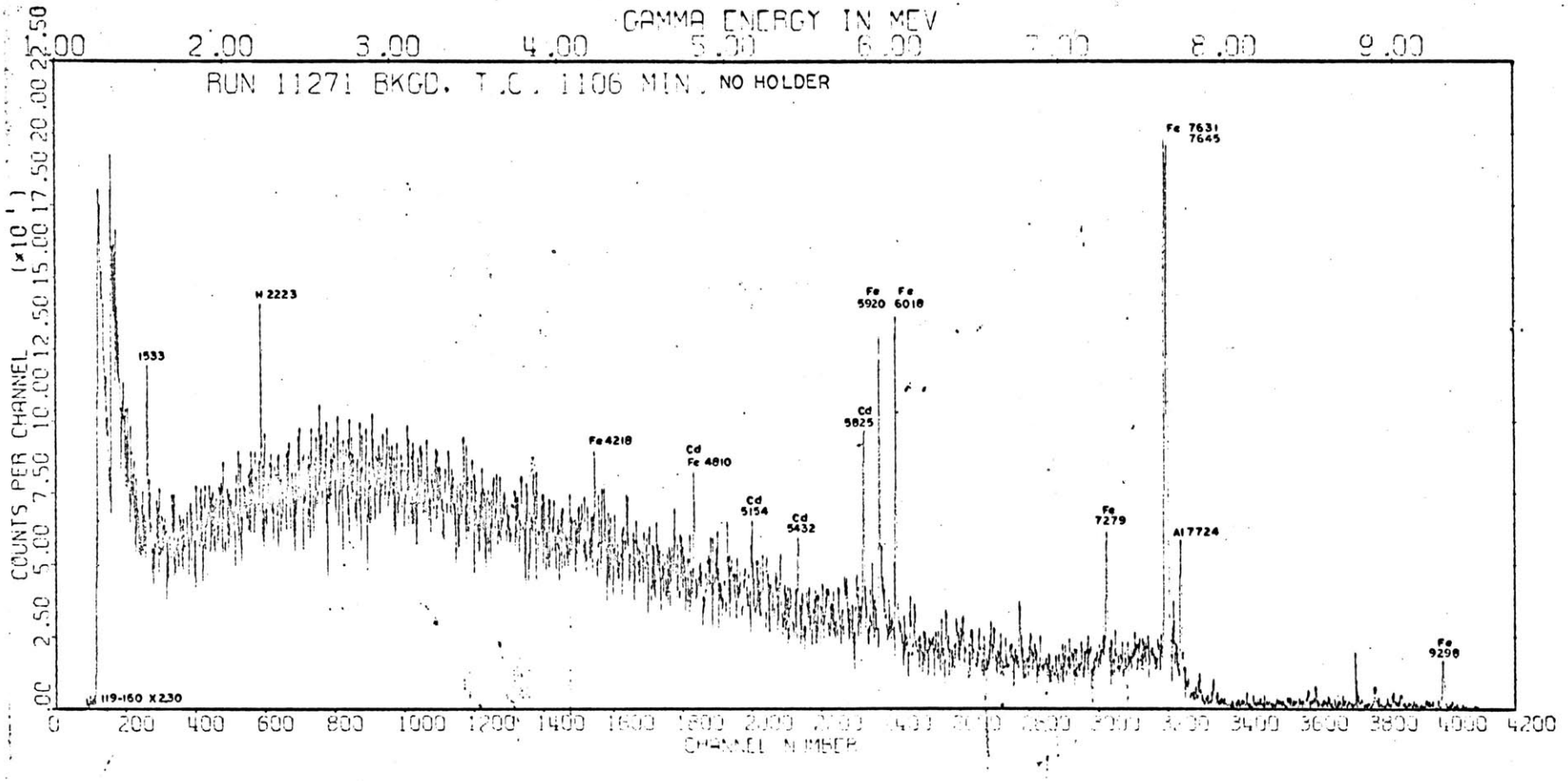

Figure 4.2 Background Pair Spectrometer Spectrum 11271

```
PARAMETERS AND INPUT DATA FOR RUN 11271  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  200
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   3.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   9.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  9.00 FWHM RANGE ERFW =  5.00
ENERGY PER CHANNEL NUMBER (KEV) = 2.080
CALIB1 E =2223.3 CNTR =  591 CORR = 591.1 FWHM =  7.03
CALIB2 E =7278.8 CNTR = 3024 CORR =3022.2 FWHM =  9.04
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.410E 10
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.927E-03
 0.915E-03 0.875E-03 0.813E-03 0.723E-03 0.637E-03
 0.550E-03 0.458E-03 0.369E-03 0.281E-03
NUMBER OF PEAKS ANALYSED = 13    J90666
```

Table 4.5 Background Pair Spectrometer Run 11271 GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1An	1532.3	264.1	56.5	0.8229	193.1	13.3	26.741	6.76	0.11E-03	8.	S *
					182.9	48.4	25.338	6.36			
2 H	2223.3	591.5	58.9	0.8089	197.0	12.5	9.140	7.03	0.33E-03	7.	S *
					215.4	28.2	9.996	7.18			
3Fe	4810.2	1834.8	35.4	0.7469	142.9	15.9	2.377	8.49	0.93E-03	9.	S *
					154.5	22.0	2.569	8.57			
4Cd	5433.6	2135.1	29.8	0.8874	156.6	12.9	2.596	11.58	0.93E-03	9.	S *
					129.2	22.8	2.141	8.51			
5Cd	5826.1	2324.2	63.0	1.6105	245.8	10.9	4.100	7.51	0.92E-03	12.	S *
					269.4	15.5	4.494	8.39			
6Fe	5921.4	2370.1	100.1	2.9215	459.2	6.2	7.692	8.60	0.92E-03	11.	S *
					425.9	12.6	7.133	8.36			
7Fe	6019.8	2417.5	105.3	2.9600	390.2	6.8	6.571	6.99	0.91E-03	10.	S *
					445.9	12.3	7.509	8.31			
8Fe	7278.8	3023.6	39.2	1.6510	203.7	10.9	4.112	9.04	0.76E-03	13.	S *
					148.5	18.5	2.997	7.43			
9Fe	7632.7	3193.4	177.0	7.0012	948.3	2.9	20.837	7.07	0.70E-03	23.	D .000
					637.1	10.9	13.999	7.07			
10Fe	7646.1	3199.9	184.7	7.3043	994.6	2.9	21.927	7.07	0.70E-03	23.	D .000
					664.7	10.8	14.654	7.07			
11Al	7723.9	3237.1	44.6	2.2719	218.1	8.5	4.901	10.36	0.68E-03	9.	S *
					158.3	18.0	3.559	6.97			
12x	8771.3	3739.1	15.8	2.8843	34.1	17.6	1.051	4.47	0.50E-03	5.	S *
					44.9	38.1	1.383	5.58			
13Fe	9298.0	3991.3	16.8	3.1134	109.1	10.3	4.142	12.37	0.41E-03	18.	S
					40.4	63.1	1.535	4.72			

Table 4.6 Background Pair Spectrometer Run 11271 GAMANL Results

4.3 Beryllium Results

Beryllium was studied to provide a check on the performance of the gamma spectrometer, to check the efficiency of the system, and to help determine the peak response function of the pair spectrometer. Table 4.7 lists the sample characteristics and run information for beryllium. The sample used consisted of a bare beryllium cylinder 1 1/2 inches in diameter by 1 inch long. All of the captures in the sample are due to beryllium-9, whose effective capture cross section is 9.5 millibarns. The average binding energy of the product nucleus is 6811.9 keV. For the sample and collimators used, it is noted that 73% of the sample was viewed for the Compton suppression run, and 98% for the pair spectrometer run. The difference being due to a slight mis-alignment of the sample for the Compton suppression data.

4.3.1 Beryllium Compton Suppression Results

Figure 4.3 shows the beryllium Compton suppression run 11201. Tables 4.8 and 4.9 give the GAMANL parameters results for this run. It is seen that a total of 31 peaks were analysed and printed out. Of these: 4 peaks are full energy capture lines from Be, 3 are double escape capture peaks, 1 is a single escape capture peak, 16 peaks are background peaks, mainly from iron capture lines, and 7 peaks are weak peaks and considered marginal.

The large neutron scattering cross section of beryllium causes the shielding material around the Be sample to experience a higher number of neutron captures than when no sample is used. This gives rise to the Ge(Li) detector seeing a larger number of resolved background lines for the Be sample than for the background runs in which no sample is used.

Beryllium is a unique sample to study in that it has very few excited levels and has only six well resolved capture gamma lines compared to some higher Z samples which have hundreds of capture lines. The Compton suppression data gives information on the 853.5 keV line of Be, and enables a comparison to be made with the pair spectrometer data for the higher energy beryllium capture lines.

TABLE 4.7 BERYLLIUM SAMPLE DATA AND RUN INFORMATION

Sample: Be Metal At. Wt.: 9.015

Wt: 54.21 gms Description: Bare Be

Holder: Al Metal Cylinder 1 1/2" diam. x 1" long

Isotope:	Be^9
Natural %:	100
Thermal Capture :	9.5 mb
Percent Captures in Natural Mixture:	100
Binding Energy of Product Nucleus: keV	6811.9

Effective Capture Cross Section: 9.5 mb

Westcott Correction: 9.5 mb

Average Binding Energy for Sample: 6811.9 keV

Flux Depression Factor: $F_1 = 1.0$ $N_T\sigma_c = 0.343\ cm^2$ $\rho x = 2.36\ gm/cm^2$

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	11201	11141
Computer Job No:	J90666	J90401
Average Thermal Flux: ϕ ($n/cm^2 sec$)	$1.83 \times 10^{+8}$	$1.83 \times 10^{+8}$
Fraction of Sample Viewed by 1" Collimator: F_2	0.73	0.98
Collimator Used: Diam.	1"	1"
Duration of Run (Min):	703	1500
Dead Time Corrected Run Time: (Min) t	670	1500
SANGLE	4.15×10^{-5}	4.15×10^{-5}
FLUXT $= F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	$1.84 \times 10^{+9}$	$5.55 \times 10^{+9}$

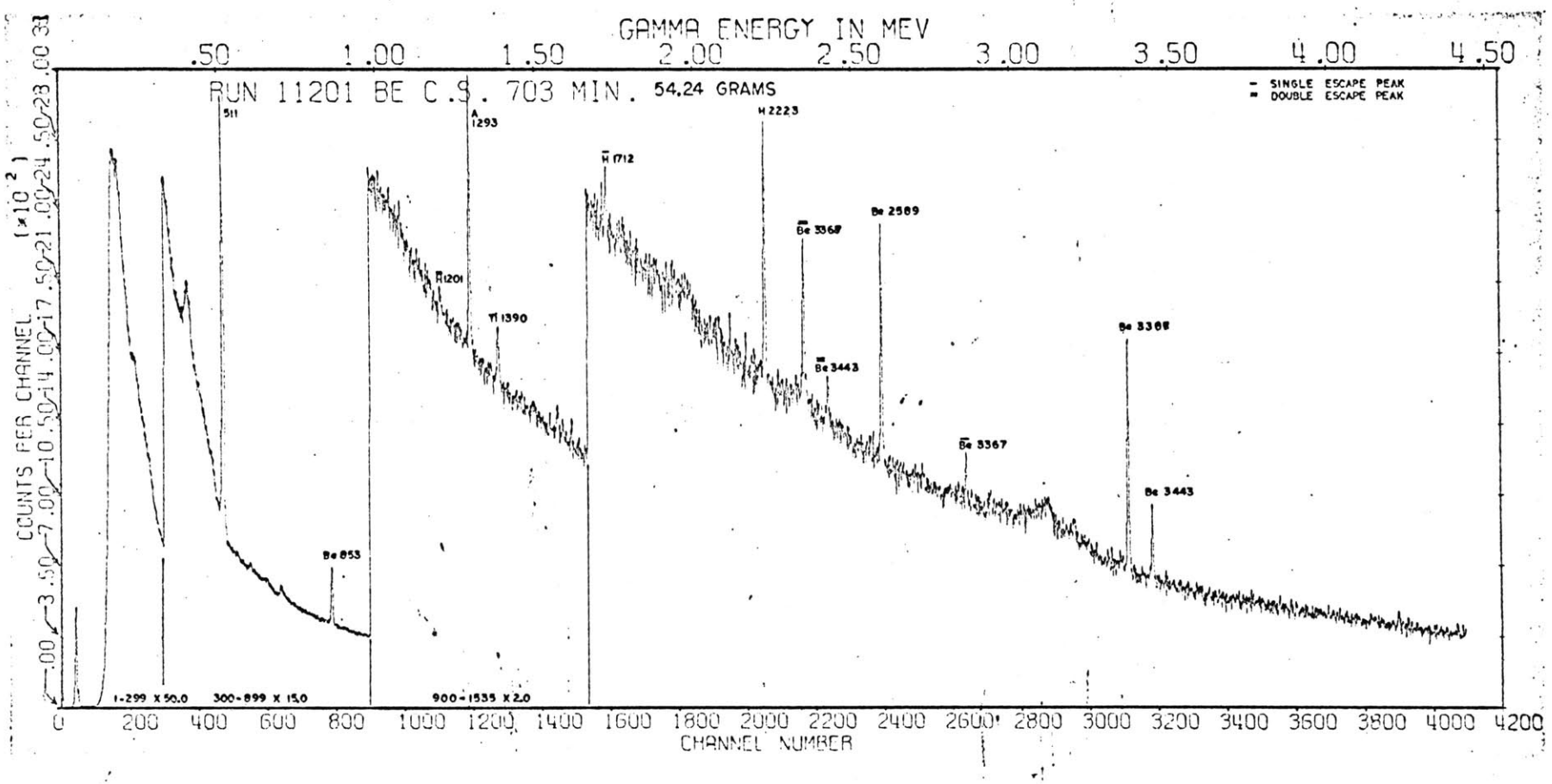

Figure 4.3 Beryllium Compton Suppression Spectrum 11201

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PARAMETERS AND INPUT DATA FOR RUN 11201  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  200
BACKGROUND CRITERION BCR * SQRT(BK) BCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  7.00 FWHM RANGE ERFW =  3.00
ENERGY PER CHANNEL NUMBER (KEV) = 1.081
CALIB1 E = 511.0 CNTR =  471 CORR = 470.0 FWHM =  5.95
CALIB2 E =3368.2 CNTR = 3114 CORR =3113.9 FWHM =  5.50
GEOMETRY FACTOR = 0.415E-04 NO OF CAPT/100 = 0.184E 10
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.426E-01 0.231E-01 0.157E-01 0.122E-01 0.100E-01
 0.917E-02 0.765E-02 0.658E-02 0.575E-02 0.518E-02
 0.456E-02 0.40CE-02 0.357E-02 0.318E-02 0.283E-02
 0.239E-02 0.218E-02 0.198E-02 0.164E-02 0.151E-02
 0.133E-02 0.116E-02 0.991E-03 0.875E-03 0.800E-03
 0.712E-03 0.628E-03 0.570E-03
NUMBER OF PEAKS ANALYSED = 31     J90666
```

Table 4.8 Beryllium Compton Suppression Run 11201 GAMANL Parameters

PEAK ANALYSIS PAGE 1

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
B	1Fe	229.6	216.6	2558.9	0.0313	12397.6	9.3	4.168	6.14	0.39E-01	15.	D	.015
						15788.6	8.1	5.308	6.14				
	2x	237.8	223.9	1217.6	0.0149	5975.9	9.3	2.060	6.14	0.38E-01	15.	D	.015
						7512.5	16.9	2.590	6.14				
B	3Ti	256.0	240.2	970.9	0.0139	3352.2	24.2	1.222	3.79	0.36E-01	7.	S	
						5972.1	19.5	2.177	6.12				
	4x	274.5	256.9	1326.9	0.0220	4871.4	13.2	1.881	4.08	0.34E-01	7.	S	*
						8142.0	13.4	3.144	6.11				
	5x	327.9	305.1	845.2	0.0234	3944.9	11.7	1.798	6.06	0.29E-01	20.	T	.004 .042
						5144.2	16.3	2.344	6.06				
B	6Ti	336.6	312.9	1229.8	0.0340	5737.7	11.7	2.686	6.06	0.28E-01	20.	T	.004 .042
						7485.2	11.3	3.504	6.06				
	7x	343.5	319.2	621.6	0.0172	2883.7	11.7	1.379	6.06	0.27E-01	20.	T	.004 .042
						3783.5	22.0	1.810	6.06				
B	8Fe	352.0	326.9	777.5	0.0242	2988.2	15.7	1.467	4.24	0.27E-01	7.	S	*
						4722.0	16.7	2.318	6.04				
B	9x	398.6	369.1	3828.0	0.1404	50664.8	3.4	28.609	6.00	0.23E-01	32.	D	.000
						23087.4	3.5	13.037	6.00				
B	10x	414.7	383.7	601.1	0.0220	7889.4	3.4	4.608	6.00	0.22E-01	32.	D	.000
						3625.3	19.8	2.117	6.00				
	11x	433.3	400.5	641.5	0.0279	3100.8	16.2	1.880	5.98	0.22E-01	15.	D	.012
						3854.1	17.2	2.337	5.98				
	12x	441.9	408.4	510.6	0.0222	2487.6	16.2	1.535	5.98	0.21E-01	15.	D	.012
						3067.6	21.5	1.893	5.98				
B	13Fe	475.8	439.4	527.7	0.0288	3048.4	17.9	2.013	5.84	0.20E-01	12.	S	*
						3155.2	18.6	2.083	5.95				
B	14Ann	511.0	471.6	32086.2	2.3715	192564.2	0.5	136.229	5.95	0.19E-01	22.	S	*
						191008.9	0.6	135.129	5.92				
B	15Cd	555.5	512.5	465.1	0.0419	3464.2	15.6	2.667	7.43	0.17E-01	16.	S	*
						2754.1	16.7	2.121	5.89				

Table 4.9 Beryllium Compton Suppression Run 11201 GAMANL Results

	NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
B	16Ge	597.3	550.8	452.8	0.0441	2080.4	15.6	1.727	5.03	0.16E-01	9.	S *
						2668.0	16.5	2.215	5.86			
B	17Fe	694.0	639.8	648.1	0.0775	5495.5	9.9	5.180	7.20	0.14E-01	19.	S *
						3776.2	10.7	3.560	5.80			
	18Be	853.5	787.3	4273.5	0.6872	23881.1	2.2	27.250	5.51	0.11E-01	21.	S *
						24475.4	2.0	27.928	5.70			
	19x	1074.7	991.8	259.2	0.0550	887.9	22.5	1.190	3.71	0.98E-02	8.	S *
						1453.0	19.7	1.947	5.58			
B	20A	1293.6	1193.8	2569.6	0.7150	13302.3	2.3	20.733	5.24	0.84E-02	15.	S *
						14146.6	2.6	22.048	5.48			
B	21Ti	1381.5	1275.2	531.9	0.1651	3573.4	8.7	6.021	6.52	0.78E-02	17.	S *
						2909.3	8.7	4.902	5.44			
	22Be DEP	1568.0	1447.6	258.6	0.0951	1307.4	14.0	2.542	5.53	0.67E-02	10.	S *
						1397.8	15.6	2.718	5.38			
B	23Fe	1612.3	1488.7	242.0	0.0936	1050.2	15.6	2.109	4.67	0.65E-02	9.	S *
						1305.2	16.2	2.621	5.37			
B	24Fe	1725.3	1593.3	327.8	0.1403	1623.4	11.4	3.526	5.13	0.60E-02	11.	S *
						1757.8	11.8	3.818	5.34			
B	25H	2222.7	2054.1	1202.2	0.7299	6645.4	2.9	19.383	5.80	0.45E-02	13.	S *
						6358.0	3.8	18.544	5.26			
	26Be DEP	2344.7	2167.9	799.0	0.5219	5164.3	5.1	16.329	5.83	0.41E-02	21.	S *
						4223.3	5.0	13.353	5.26			
	27Be DEP	2420.5	2238.2	202.5	0.1398	817.8	15.1	2.709	4.39	0.40E-02	9.	S *
						1070.6	15.0	3.546	5.26			
	28Be	2588.8	2394.0	1124.7	0.9059	5913.2	3.2	21.553	5.29	0.36E-02	15.	S *
						5957.5	3.7	21.715	5.27			
	29Be SEP	2856.0	2640.7	210.9	0.2049	886.6	11.9	3.756	4.48	0.31E-02	9.	S *
						1125.5	12.8	4.769	5.31			
	30Be	3368.2	3113.7	1126.7	1.6588	6270.2	2.6	37.110	5.50	0.22E-02	17.	S *
						6187.3	3.5	36.619	5.47			
	31Be	3444.3	3183.9	359.5	0.5436	1637.9	5.9	9.987	4.86	0.21E-02	10.	S *
						1985.7	7.4	12.107	5.50			

Table 4.9 (Continued) Be CS

4.3.2 Beryllium Pair Spectrometer Results

Figure 4.4 shows the beryllium pair spectrometer spectrum of run 11141. Tables 4.10 and 4.11 give the GAMANL and GAMABC parameters and GAMANL results respectively. Table 4.12 presents the GAMABC results. The five peaks of beryllium are seen quite clearly in the spectrum of Figure 4.4, as well as the iron background peaks and some titanium peaks.

The continuum is seen to be quite low and flat over the energy range from 1.5 MeV to 9.5 MeV. This example of a well resolved spectrum was analysed by GAMABC in order to test the code's performance with a well resolved known spectrum.

Table 4.12 shows the total fraction of the sample binding energy as computed by GAMABC to be 110.2%, which is within the quoted error of ± 15% from 100%. This is broken into 100.9% being due to the well resolved capture peaks having energies greater than 1.5 MeV and 3.4% due to the 853.5 keV line using the results of the Compton suppression data. The remaining 5.9% is caused by the counts in the continuum which have been analysed as being due to unresolved capture gammas in beryllium.

As described in Section 3.6, the continuum is analysed by correcting for the peak response, background, and bin response counts in the observed continuum. The GAMABC

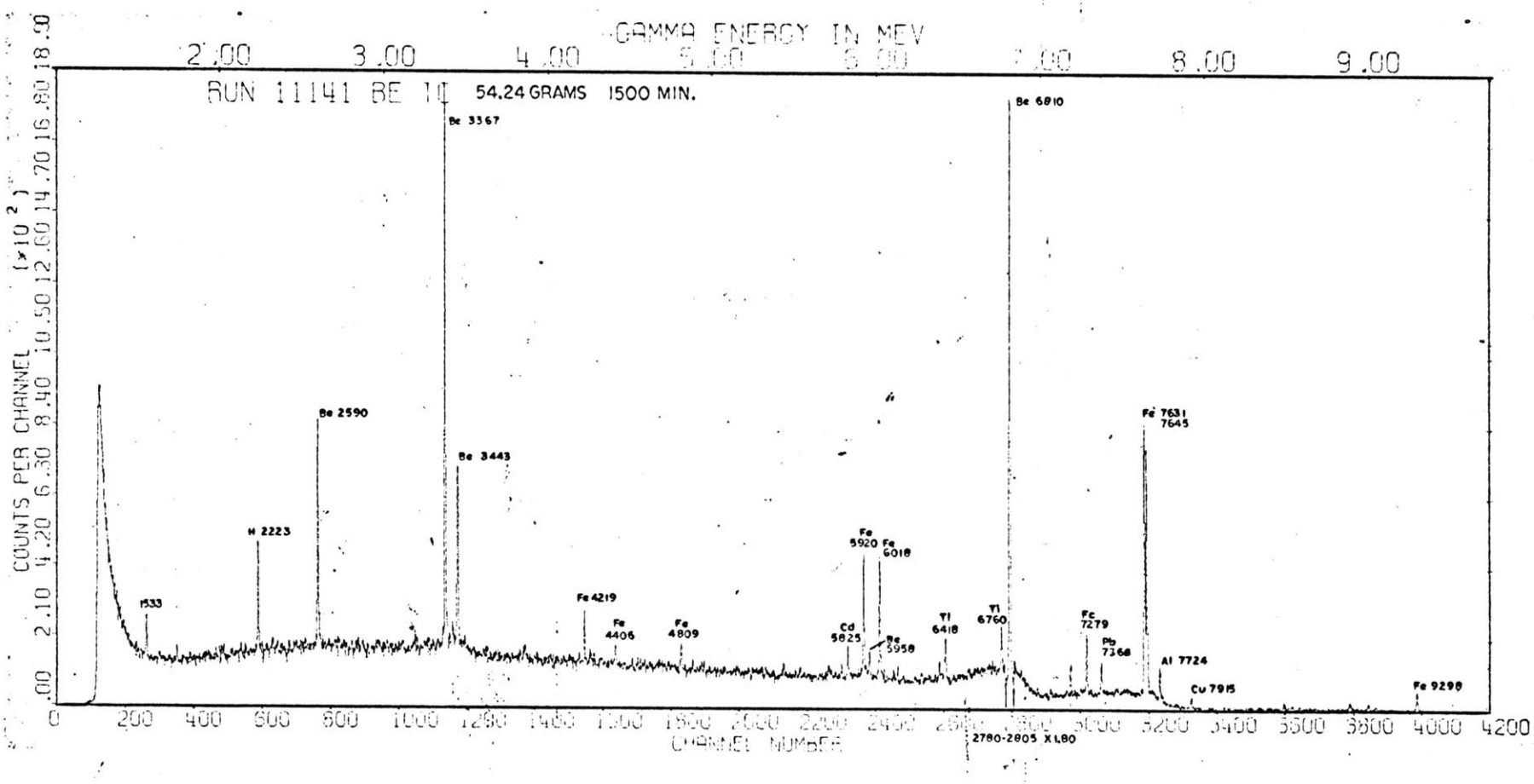

Figure 4.4 Beryllium Pair Spectrometer Spectrum 11141

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PARAMETERS AND INPUT DATA FOR RUN 11141  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  163
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR. =  30.0
FIRST PEAK FWHM(KEV) FPS =  6.50 FWHM RANGE ERFW =  2.00
ENERGY PER CHANNEL NUMBER (KEV) = 2.081
CALIB1 E =2223.3 CNTR =  588 CORR = 588.0 FWHM =  7.18
CALIB2 E =7367.7 CNTR = 3062 CORR =3060.3 FWHM =  7.27
GEOMETRY FACTOR = 0.415E-04 NO OF CAPT/100 = 0.555E 10
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.928E-03
 0.925E-03 0.910E-03 0.840E-03 0.742E-03 0.640E-03
 0.555E-03 0.460E-03 0.370E-03 0.282E-03
NUMBER OF PEAKS ANALYSED = 30     J90401

GAMABC PEAK RESPONSE FUNCTION PARAMETERS
F2 = 0.0012  x AREA        F5 = 0.0023 x AREA
F3 = 0.0007  x AREA        F8 = 0.0066 x AREA
LOW CH = IMAX              MID CH = 900
W1 = 250 + 125(E - 6800)/ 850 for E > 6810 keV
W1 = 120 + 130(E - 2200)/4610 for E ≤ 6810 keV
W2 = 0.0002 x AREA + 1.0
W3 = 70
BAKFAC = 1.350     BIN WIDTH = 20 Chs     RED = 1.132
```

Table 4.10 Beryllium Pair Spectrometer Run 11141
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

NO		ENERGY	PK CNT	HEIGHT	H TO B	AREA-S / AREA-G	ERR-S / ERR-G	INT-S / INT-G	FWHM-M / FWHM-C	EFF(E)	BASE	TYPE
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
B	1	Anl 533.1	261.8	125.7	0.8316	479.6	11.1	18.700	7.12	0.11E-03	12.	S *
						476.5	11.3	18.580	7.39			
B	2	H 2223.3	588.5	333.9	1.9127	1191.0	4.5	15.593	7.18	0.33E-03	9.	S *
						1211.6	6.1	15.863	7.07			
	3	Be 2589.5	764.1	662.7	3.3262	2362.9	3.0	22.601	6.89	0.45E-03	11.	S *
						2360.8	4.2	22.581	6.94			
	4	Be 3366.9	1137.4	1640.6	7.1200	5595.7	1.7	34.470	6.73	0.70E-03	11.	S *
						5686.5	2.6	35.030	6.75			
	5	Be 3443.0	1173.9	544.1	2.8240	2131.7	3.4	12.740	7.18	0.73E-03	12.	S *
						1882.5	4.6	11.251	6.74			
	6	x 4026.9	1454.3	46.8	0.3989	112.0	23.9	0.561	4.87	0.87E-03	5.	S
						160.8	21.7	0.805	6.69			
B	7	Fe 4219.1	1546.4	147.7	1.0493	398.2	8.4	1.955	5.51	0.88E-03	6.	S *
						506.8	9.9	2.487	6.68			
B	8	Fe 4406.3	1636.7	61.4	0.4472	227.9	16.0	1.100	6.54	0.90E-03	8.	S *
						210.7	18.4	1.017	6.69			
B	9	Fe 4809.4	1830.6	77.5	0.6336	272.6	13.0	1.280	7.26	0.92E-03	8.	S *
						267.5	15.1	1.256	6.72			
B	10	Cd 5433.4	2131.0	39.9	0.3909	107.5	23.2	0.503	5.63	0.93E-03	6.	S *
						140.1	23.6	0.655	6.84			
B	11	Cd 5824.8	2319.4	83.9	0.7752	251.3	12.3	1.176	6.03	0.93E-03	7.	S *
						299.0	13.9	1.400	6.95			
B	12	Fe 5920.9	2365.7	340.7	2.9368	1155.0	4.1	5.414	6.77	0.93E-03	9.	S *
						1220.5	5.8	5.721	6.98			
	13	x 5957.3	2383.2	79.7	0.7453	273.4	12.3	1.282	6.92	0.93E-03	8.	S *
						286.2	14.3	1.342	6.99			
B	14	Fe 6019.1	2412.9	348.5	3.2099	1259.9	4.5	5.911	6.82	0.93E-03	13.	S *
						1254.8	5.7	5.887	7.01			
	15	x 6128.2	2465.6	40.4	0.4744	98.9	20.8	0.463	4.93	0.93E-03	5.	S *
						146.3	22.2	0.686	7.05			

Table 4.11 Beryllium Pair Spectrometer Run 11141 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
16x	6381.0	2587.3	49.7	0.5225	174.5	16.0	0.825	7.06	0.92E-03	7.	S *	
					182.7	19.6	0.863	7.16				
B 17Ti	6418.5	2605.2	120.8	1.2315	502.7	8.4	2.382	8.24	0.92E-03	11.	S *	
					444.9	10.7	2.108	7.17				
B 18Ti	6760.2	2769.5	132.3	1.0773	570.5	8.7	2.824	8.36	0.88E-03	12.	S *	
					498.4	10.5	2.467	7.34				
19x	6793.4	2785.6	60.4	0.4978	233.4	1.1	1.161	7.36	0.87E-03	23.	T .000	.000
					228.1	18.0	1.135	7.36				
20Be	6809.8	2793.4	3241.0	26.7301	12608.3	1.1	62.926	7.36	0.87E-03	23.	T .000	.000
					12247.6	1.8	61.126	7.36				
21x	6825.0	2800.7	69.5	0.5728	275.9	1.1	1.380	7.36	0.87E-03	23.	T .000	.000
					262.5	16.3	1.313	7.36				
B 22Fe	7278.7	3018.9	172.9	3.0687	655.2	6.1	3.620	7.27	0.79E-03	13.	S *	
					677.0	8.2	3.740	7.63				
B 23Pb	7367.7	3061.8	84.4	1.5479	315.9	9.5	1.785	7.27	0.77E-03	10.	S *	
					332.9	12.4	1.881	7.68				
B 24Fe	7631.2	3188.0	777.1	14.6629	3122.6	1.6	18.999	7.86	0.71E-03	20.	D .000	
					3135.1	3.7	19.075	7.86				
B 25Fe	7645.5	3194.9	717.5	13.5383	2874.2	1.6	17.562	7.86	0.71E-03	20.	D .000	
					2894.7	3.8	17.687	7.86				
B 26Al	7724.1	3232.5	93.9	2.2816	338.3	8.2	2.116	7.01	0.69E-03	10.	S *	
					381.7	11.3	2.387	7.92				
B 27Cu	7916.4	3324.8	31.0	2.7720	130.5	11.0	0.864	7.71	0.66E-03	10.	S *	
					128.4	18.8	0.850	8.06				
B 28Cr	8485.7	3597.2	16.5	2.1825	64.7	15.1	0.504	7.97	0.56E-03	10.	S *	
					72.1	25.6	0.562	8.51				
B 29Fe	8887.5	3789.7	18.6	1.7381	79.5	14.7	0.718	9.35	0.48E-03	9.	S *	
Cr					84.7	25.0	0.765	8.87				
B 30Fe	9298.2	3986.2	52.0	5.5405	227.7	7.3	2.435	9.00	0.41E-03	10.	S *	
					247.1	14.4	2.642	9.26				

Table 4.11 (Continued) Be PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	241	372.6	8706.2	7090.3	1500.0	11.54	48.6
		794.7	-422.1			0.0	
2	362	-113.8	9200.0	6653.3	1750.0	-2.25	159.2
		504.5	-618.3			0.0	
3	482	-168.1	10178.5	7467.8	2000.0	-2.43	113.9
		574.5	-742.6			0.0	
4	602	-250.9	11125.7	7929.7	2250.0	-2.88	79.1
		513.6	-764.5			0.0	
5	722	-106.9	11767.1	8783.4	2500.0	-1.00	192.4
					2589.5	22.60	3.0
		558.2	-665.1			22.60	
6	842	-352.8	11544.2	7680.8	2750.0	-2.79	56.6
		541.6	-894.4			0.0	
7	962	-888.2	11045.0	8501.0	3000.0	-6.11	22.7
		261.1	-1149.4			0.0	
8	1082	-200.0	10655.3	10676.4	3250.0	-1.24	105.7
					3366.9	34.47	1.7
					3443.0	12.74	3.4
		915.7	-1115.8			47.21	
9	1203	522.2	9510.7	7600.4	3500.0	2.91	36.0
		863.0	-340.8			0.0	
10	1323	485.7	8812.1	7160.0	3750.0	2.48	37.5
		863.5	-377.8			0.0	
11	1443	1.0	8165.2	6834.5	4000.0	0.01******	
					4026.9	0.56	23.9
		571.6	-570.5			0.56	
12	1563	97.6	7400.6	6902.3	4250.0	0.47	176.5
					4406.3	1.10	16.0
		595.1	-497.5			1.10	
13	1683	384.7	6431.7	6980.4	4500.0	1.83	43.6
		824.6	-439.9			0.0	
14	1803	285.9	5620.8	6867.4	4750.0	1.33	56.4
		680.0	-394.1			0.0	
15	1923	-181.1	5504.1	6295.1	5000.0	-0.85	86.7
		447.9	-629.0			0.0	
16	2044	-15.2	4382.7	6508.9	5250.0	-0.07	994.7
		548.5	-563.7			0.0	
17	2164	-93.7	3641.3	7007.3	5500.0	-0.44	159.1
		429.9	-523.6			0.0	
18	2284	-26.9	3257.1	7865.1	5750.0	-0.13	565.4
					5957.3	1.28	12.3
		458.9	-485.8			1.28	
19	2404	258.7	2679.1	6946.3	6000.0	1.21	55.0
					6128.2	0.46	20.8
		609.8	-351.1			0.46	

Table 4.12 Beryllium Pair Spectrometer Run 11141
GAMAEC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 2

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
20	2524	-12.4	2355.7	7307.1	6250.0	-0.061	148.1
					6381.0	0.82	16.0
		478.1	-490.5			0.82	
21	2644	21.9	1844.3	10275.5	6500.0	0.11	726.3
		520.8	-498.9			0.0	
22	2764	166.4	1445.1	8293.1	6750.0	0.84	86.4
					6793.4	1.16	1.1
					6809.8	62.93	1.1
					6825.0	1.38	1.1
		680.0	-513.7			65.47	
23	2885	121.3	952.5	3588.8	7000.0	0.65	81.5
		407.4	-286.1			0.0	
24	3005	240.8	832.3	4485.4	7250.0	1.36	44.2
		458.4	-217.5			0.0	
25	3125	24.3	1142.8	3957.1	7500.0	0.15	427.5
		313.6	-289.3			0.0	
26	3245	45.9	470.1	273.7	7750.0	0.30	92.6
		183.8	-137.9			0.0	
27	3365	28.4	163.2	117.6	8000.0	0.20	97.7
		117.3	-88.9			0.0	
28	3485	-24.1	215.9	58.4	8250.0	-0.18	116.8
		108.8	-132.9			0.0	
29	3605	17.0	178.3	118.4	8500.0	0.14	168.7
		121.8	-104.9			0.0	
30	3726	-8.5	209.3	21.0	8750.0	-0.08	327.6
		149.9	-158.4			0.0	
31	3846	25.0	105.9	127.7	9000.0	0.25	100.9
		97.8	-72.8			0.0	
32	3966	71.4	0.5	53.5	9250.0	0.86	22.3
		109.0	-37.6			0.0	
33	4086	-1.1	3.7	-3.7	9500.0	-0.01	163.6
		1.0	-2.0			0.0	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 6811.90
UNRES = 14.8 -8.9 = 5.9%RES = 100.9%TOTAL = 107.4%
CS UNRES (EST) = 0.0% CS RES = 3.4% TOTAL ALL = 110.2%

Table 4.12 (Continued) Be PS GAMAEC Results

Table 4.12 shows the result of this analysis for the beryllium data. Since beryllium has a spectrum that consists of almost no unresolved gamma rays, the continuum analysis should yield zero values for the energy bin intensities which are given in Table 4.12. However in the analyis of the data, small fluctuations in the data will give rise to small positive and negative results for the counts in a bin. Upon converting these counts to bin intensity, small positive and negative values can arise, as are indicated by the data in Table 4.12. The amount and magnitude of these intensity variations give an indication of how well the beryllium continuum has been accounted for by the analysis.

Summing the product of the positive energy bin intensity values times an average bin intensity and dividing by the binding energy gives the percent fraction accounted for by the positive intensity values of the bins, and a similar calculation is true for the negative bin intensity values. These two calculations yield respectively: + 14.8% and - 8.9% as shown in Table 4.12. The sum of these two values gives the 5.9% net total that is caused by the beryllium continuum. Since beryllium is expected to be entirely resolved, these numbers show the GAMABC code performance in analysing a continuum which should be negligible.

In the 104.3% (100.9% + 3.4%) as listed from GAMABC

for the total resolved peak contribution, five relatively low peaks were counted in the total, as well as two satellite peaks around the 6809.8 keV line. The five peaks are listed in Table 4.12 with energies: 4026.9, 4406.3, 5057.3, 6128.2, and 6381.0 keV, and they contribute an extra 3.3% to the calculated binding energy fraction. The two satellite peaks at energies: 6793.4, and 6825.0 keV, give 2.3% to the binding energy fraction. If these seven peaks are deleted from the calculation the fraction of the binding energy attributed to the resolved peaks would be 98.7%.

4.3.3 Beryllium Comparison of Results

Table 4.13 shows a comparison of the results of this work with the published capture intensities for beryllium. The energies of the gamma lines as found in this work are also given. The main reference used in Table 4.13 is Nuclear Data (ND-1).

As discussed in Section 2.4.6 and 2.4.5 , the efficiency curves for the Compton suppression data, Figure 2.12, and for the pair spectrometer data, Figure 2.11, were determined by using the values of the intensities of the beryllium lines. The efficiency data which was used for the 9CH2 spectrometer by Orphan (O-1) was corrected for the masonite absorption in the gamma beam and used as an estimate for the 4TH1 efficiency curves. The data were analysed by GAMANL, and the intensities so obtained were

Table 4.13 Beryllium Comparison of Results

Intensity, I, given in number of gamma rays of energy E emitted per 100 thermal neutron captures in the Be sample.

Present Work		MIT-NE-85	Nuclear Data Tables (ND-1)		
		R-1	Jarczyck	Motz	Draper
			61Jal9	62Mo23	63Dr02
Energy keV	semi I	semi I	s pr I	s Cp I	scin I
6809.8	62.9	62.4	70	62	65
5957.3	1.3	2.0	2	1.4	2
3443.3	12.7	11.8	15	11	11
3368.2	34.5	34.2	28	37	28
2588.8	22.6	24.1	17	28	21
853.5	27.3	25.3	16		24

then compared to those listed in MITNE-85 for beryllium, which agreed well with other published data. An improvement of the results was obtained by a slight shifting of both the Compton suppression full energy peak efficiency curve and the pair spectrometer double escape peak efficiency curves. The amount of this shift for each curve is shown in the Figures 2.11 and 2.12 mentioned above. After the efficiency curves had been corrected, the beryllium data were reanalysed. The results from this analysis are those given in this Section 4.3. The intensities listed in Table 4.13 show good agreement with those of MITNE-85 and with the other published intensities.

4.4 Iron Results

A sample of iron oxide was studied to confirm the efficiency results obtained from the beryllium, and to help determine the peak response function of the pair spectrometer. The iron data were also used to check the performance of the GAMABC code in analysis of the continuum. Table 4.14 gives the sample characteristics and run information for the iron sample. The iron oxide powder filled the poly vial to 1/2 full. Iron-56 contributes about 94% of the captures in the sample. The effective capture cross section used was 2.62 milli-barns, and the average sample binding energy was 7848.0 keV. For this sample, 90% of the sample was seen for the Compton suppression data, and 74% of the sample was seen for the pair spectrometer data. This difference is due to slight mis-alignment of the sample position in the pair spectrometer case.

4.4.1 Iron Compton Suppression Results

Figure 4.5 shows the iron Compton suppression spectrum, run 12171. Tables 4.15 and 4.16 present the GAMANL parameters and GAMANL results respectively. It is seen that 83 peaks were analysed and printed out. Of these: 53 peaks are full energy capture peaks from iron, 2 are single escape peaks from iron, 3 are doubles escape peaks from iron, 6 are background or trace elements (Ti), and 19 are marginal peaks and tentatively assigned to iron.

TABLE 4.14 IRON SAMPLE DATA AND RUN INFORMATION

Sample: Fe_2O_3 At. Wt.: 55.85

Wt: 40.3 gms Fe Description: 54.0 gms Fe_2O_3 Powder in Poly Vial 1 1/4" diam x 2" Vial 1/2 full

Holder: Al

Isotope:	Fe^{54}	Fe^{56}	Fe^{57}
Natural %:	5.84	91.66	2.19
Thermal Capture :	2.3b	2.7b	2.5
Percent Captures in Natural Mixture:	5	94	2
Binding Energy of Product Nucleus: keV	9299.5	7646.5	10042.5

Effective Capture Cross Section: 2.62b

Westcott Correction: σ_c = 2.62 b

Average Binding Energy for Sample: 7848.0 keV

Flux Depression Factor: F_1 = 0.93 $N_T\sigma_c$ = 1.07 cm^2 $\rho\bar{x}$ = 2.13 gm/cm^2

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	12171	11071
Computer Job No:	J60371	J60323
Average Thermal Flux: ϕ ($n/cm^2 sec$)	$1.83 \times 10^{+8}$	$1.83 \times 10^{+8}$
Fraction of Sample Viewed by 1" Collimator: F_2	0.90	0.74
Collimator Used: diam.	1/2"	1/2"
Duration of Run (Min):	640	1440
Dead Time Corrected Run Time: (Min) t	570	1440
SANGLE	1.58×10^{-5}	1.58×10^{-5}
$FLUXT = F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	$5.60 \times 10^{+10}$	$1.17 \times 10^{+11}$

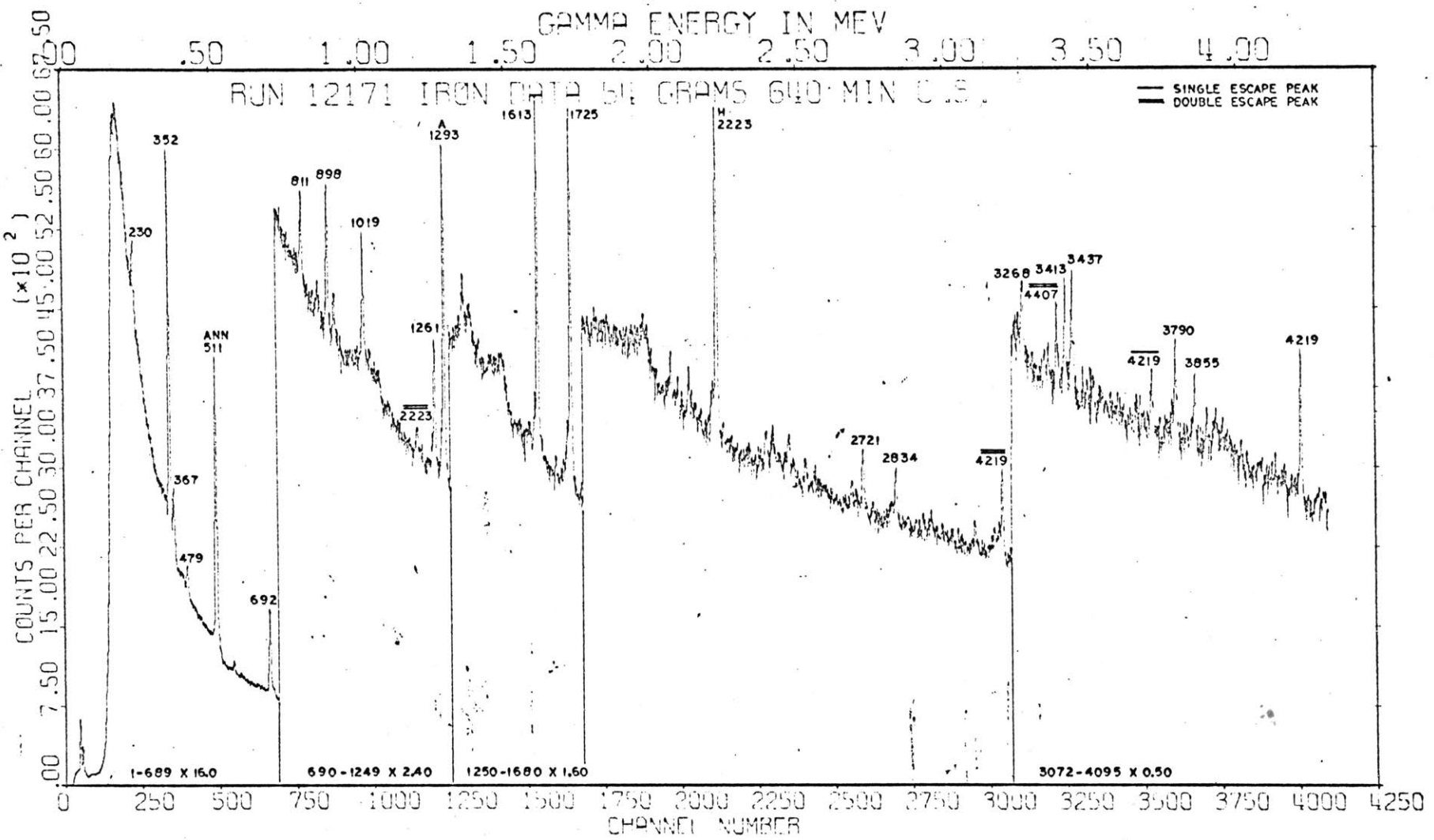

Figure 4.5 Iron Compton Suppression Spectrum 12171

```
PARAMETERS AND INPUT DATA FOR RUN 12171  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  184
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  7.50 FWHM RANGE ERFW =  3.00
ENERGY PER CHANNEL NUMBER (KEV) = 1.053
CALIB1 E = 511.0 CNTR =  490 CORR = 488.4 FWHM =  6.48
CALIB2 E =2223.3 CNTR = 2115 CORR =2115.0 FWHM =  7.04
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.560E 11
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.477E-01 0.256E-01 0.171E-01 0.132E-01 0.106E-01
 0.975E-02 0.809E-02 0.696E-02 0.603E-02 0.541E-02
 0.476E-02 0.418E-02 0.371E-02 0.330E-02 0.294E-02
 0.248E-02 0.224E-02 0.205E-02 0.169E-02 0.155E-02
 0.137E-02 0.120E-02 0.102E-02 0.900E-03 0.832E-03
 0.740E-03 0.649E-03 0.588E-03
NUMBER OF PEAKS ANALYSED = 83   .J60371
```

Table 4.15 Iron Compton Suppression Run 12171
GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
1x	191.2	192.5	1576.4	0.0176	8412.5	8.7	0.193	5.53	0.49E-01	15.	D .002
					9058.7	13.7	0.208	5.53			
2x	200.5	201.0	2177.8	0.0243	12002.6	8.7	0.284	5.53	0.48E-01	15.	D .002
					12514.4	10.0	0.296	5.53			
3x	208.6	208.5	997.7	0.0122	2683.6	24.8	0.065	2.81	0.46E-01	5.	S
					5745.0	20.6	0.139	5.55			
4Fe	230.4	228.5	9525.4	0.1302	54753.6	2.3	1.419	5.67	0.43E-01	14.	S *
					55043.0	2.3	1.427	5.56			
5x	243.2	240.3	882.9	0.0136	3576.1	17.2	0.096	5.58	0.42E-01	14.	D .002
					5116.0	20.7	0.138	5.58			
6x	251.2	247.6	1167.0	0.0179	4742.9	17.2	0.131	5.58	0.41E-01	14.	D .002
					6762.2	15.7	0.187	5.58			
7x	260.3	256.1	897.8	0.0148	2384.5	24.0	0.068	2.90	0.40E-01	5.	S
					5212.7	19.7	0.148	5.59			
8x	287.1	280.8	1043.8	0.0203	4068.6	14.6	0.126	4.18	0.36E-01	7.	S *
					6085.6	15.7	0.188	5.61			
9x	294.9	288.1	1347.4	0.0273	4466.5	13.0	0.142	3.50	0.36E-01	7.	S *
					7865.4	12.0	0.250	5.62			
10x	302.6	295.3	819.8	0.0173	3176.6	19.9	0.103	4.10	0.35E-01	8.	S *
					4791.0	19.1	0.156	5.63			
11x	329.6	320.3	901.5	0.0204	3204.5	17.1	0.113	3.77	0.32E-01	7.	S *
					5290.4	16.8	0.187	5.65			
12x	338.6	328.7	1299.5	0.0305	4939.3	10.9	0.180	4.06	0.31E-01	7.	S *
					7636.0	11.6	0.278	5.66			
13Fe	352.1	341.2	55031.1	1.3743	300135.0	0.4	11.404	5.43	0.30E-01	17.	S *
					324023.6	0.5	12.312	5.67			
14Fe	366.2	354.3	7924.2	0.2142	38551.1	2.1	1.530	5.02	0.28E-01	12.	S *
					46754.4	2.1	1.856	5.68			
15x	391.3	377.6	594.6	0.0189	1769.5	23.3	0.076	3.18	0.26E-01	6.	S *
					3521.0	21.5	0.151	5.70			

Table 4.16 Iron Compton Suppression Run 12171 GAMANL Results

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
16Fe	398.3	384.2	934.9	0.0303	3035.3	15.2	0.133	3.45	0.26E-01	7.	S *
					5541.8	13.7	0.243	5.71			
17Fe	411.5	396.5	3922.1	0.1336	22892.8	3.9	1.032	5.83	0.25E-01	16.	S *
					23292.5	3.5	1.050	5.72			
18Fe	432.1	415.7	617.1	0.0230	1851.9	20.5	0.087	3.16	0.24E-01	6.	S *
					3675.3	19.2	0.173	5.74			
19Fe	442.1	425.1	594.8	0.0230	3201.6	17.4	0.154	6.18	0.23E-01	10.	S *
					3547.3	19.6	0.171	5.74			
20Fe	450.0	432.5	516.4	0.0205	1812.7	22.9	0.089	3.74	0.23E-01	7.	S *
					3083.5	22.2	0.151	5.75			
21Fe	458.8	440.8	626.1	0.0253	2490.0	18.3	0.124	4.25	0.23E-01	8.	S *
					3742.6	18.2	0.186	5.76			
22Fe	474.7	455.7	489.1	0.0206	1959.5	22.8	0.101	4.28	0.22E-01	8.	S *
					2930.3	22.7	0.151	5.77			
B 23Ann	511.0	489.9	43536.7	2.0696	310483.2	0.5	17.219	6.48	0.20E-01	32.	S *
					262085.9	0.5	14.535	5.80			
24Fe	569.4	544.9	1620.0	0.0944	7803.4	9.1	0.486	4.62	0.18E-01	17.	S *
					9825.8	6.2	0.611	5.84			
25Fe	594.1	568.2	532.2	0.0326	2330.7	17.5	0.152	4.71	0.17E-01	9.	S *
					3237.9	17.5	0.211	5.86			
26Fe	628.0	600.2	386.8	0.0253	1538.5	23.3	0.105	4.25	0.16E-01	8.	S *
					2363.0	23.1	0.162	5.88			
27Fe	652.2	623.1	518.3	0.0349	1920.1	16.7	0.136	3.91	0.16E-01	7.	S *
					3175.7	17.2	0.224	5.90			
28Fe	692.5	661.2	12328.1	0.8984	82420.6	1.6	6.135	5.93	0.15E-01	32.	D .000
					75937.1	1.1	5.653	5.93			
29Fe	704.0	672.2	1078.3	0.0786	7231.2	1.6	0.546	5.93	0.15E-01	32.	D .000
					6642.0	8.3	0.502	5.93			
30Fe	737.9	704.3	355.6	0.0283	1091.7	23.9	0.086	3.25	0.14E-01	6.	S *
					2199.8	22.9	0.174	5.96			
31Fe	811.0	773.8	1770.2	0.1536	11598.9	4.8	1.004	6.30	0.13E-01	16.	S *
					11037.5	4.9	0.956	6.00			

Table 4.16 (Continued) Fe CS

PEAK ANALYSIS PAGE 3

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
32Fe	838.1	799.4	358.8	0.0332	1354.1	20.1	0.121	4.02	0.13E-01	7.	S *
					2243.3	21.1	0.201	6.02			
33Fe	847.2	808.1	384.0	0.0356	1674.9	18.0	0.152	4.68	0.12E-01	8.	S *
					2402.9	19.8	0.218	6.03			
34Fe	864.4	824.4	400.4	0.0367	1415.8	21.4	0.131	3.77	0.12E-01	8.	S *
					2509.8	19.1	0.232	6.04			
35Ti	871.8	831.5	388.3	0.0363	1295.7	20.9	0.121	3.57	0.12E-01	7.	S *
					2435.7	19.5	0.227	6.04			
36Fe	898.2	856.5	3171.0	0.3034	19364.5	2.9	1.864	5.77	0.12E-01	17.	S *
					19943.6	2.9	1.920	6.06			
37Fe	920.5	877.5	913.9	0.0895	5080.9	8.6	0.501	5.63	0.11E-01	13.	S *
					5760.0	8.5	0.568	6.07			
38Fe	940.9	896.8	336.4	0.0346	1068.5	24.2	0.108	3.36	0.11E-01	7.	S *
					2124.1	21.4	0.214	6.08			
39Fe	1007.4	960.1	320.1	0.0337	2309.2	4.9	0.246	6.12	0.11E-01	31.	D .000
					2034.4	22.2	0.217	6.12			
40Fe	1018.7	970.9	2932.6	0.3090	21147.7	4.9	2.257	6.12	0.11E-01	31.	D .000
					18637.7	3.0	1.989	6.12			
41Fe	1041.5	992.6	386.3	0.0409	1370.8	20.6	0.147	3.77	0.10E-01	8.	S *
					2460.8	18.5	0.264	6.13			
42Fe	1109.3	1056.5	294.9	0.0356	1138.9	23.2	0.125	4.12	0.10E-01	8.	S *
					1888.7	22.6	0.208	6.17			
B 43H	1201.0	1143.4	664.9	0.0889	4829.1	8.8	0.559	6.90	0.97E-02	15.	S *
DEP					4287.5	10.0	0.496	6.21			
44Fe	1253.3	1193.2	553.2	0.0770	3312.5	3.7	0.403	6.23	0.93E-02	24.	D .021
					3581.2	11.6	0.436	6.23			
45Fe	1260.8	1200.3	3005.0	0.4183	17862.0	3.7	2.190	6.23	0.92E-02	24.	D .021
					19452.3	2.7	2.385	6.23			
B 46A	1293.8	1231.7	7625.1	1.0852	52878.9	1.4	6.690	5.95	0.89E-02	27.	S *
					49474.4	1.4	6.259	6.25			
47Fe	1359.4	1293.9	720.4	0.1039	4888.5	7.9	0.657	7.28	0.84E-02	14.	S *
					4692.4	9.0	0.631	6.27			

Table 4.16 (Continued) Fe CS

PEAK ANALYSIS PAGE 4

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE		
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN			
48x	1412.4	1344.1	329.9	0.0512	1230.7	19.0	0.173	3.93	0.80E-02	8.	S	*	
					2154.9	18.1	0.303	6.29					
49Fe	1603.1	1525.5	670.9	0.1334	4495.7	2.5	0.729	6.35	0.69E-02	36.	D	.000	
					4422.7	8.4	0.718	6.35					
50Fe	1613.3	1535.2	5172.2	1.0283	34959.3	2.5	5.718	6.35	0.69E-02	36.	D	.000	
					34094.2	1.8	5.576	6.35					
51Fe	1673.8	1592.7	303.4	0.0652	1347.8	17.7	0.231	4.63	0.66E-02	10.	S	*	
					2004.4	16.9	0.343	6.36					
52x	1699.4	1617.1	230.5	0.0492	723.6	22.1	0.126	3.31	0.65E-02	6.	S	*	
					1524.3	22.0	0.266	6.37					
B 53H	1714.0	1630.9	852.5	0.1837	5731.6	1.9	1.010	6.37	0.64E-02	31.	D	.000	
SEP					5640.8	6.6	0.994	6.37					
54Fe	1725.6	1642.0	5500.1	1.1855	37014.6	1.9	6.578	6.37	0.63E-02	31.	D	.000	
					36393.0	1.7	6.468	6.37					
55Fe	2067.6	1967.0	305.6	0.0818	1295.6	15.2	0.282	4.43	0.52E-02	9.	S	*	
					2033.4	15.3	0.442	6.41					
56Fe	2129.5	2026.1	393.7	0.1119	2212.6	10.9	0.500	5.96	0.50E-02	12.	S	*	
					2620.4	11.8	0.593	6.41					
57x	2194.9	2088.3	205.6	0.0624	750.8	20.2	0.177	3.89	0.48E-02	7.	S	*	
					1368.4	20.9	0.323	6.41					
58x	2205.5	2098.5	292.1	0.0899	2226.8	2.8	0.529	6.41	0.47E-02	38.	T	.154	.000
					1943.3	15.0	0.462	6.41					
59x	2209.8	2102.6	468.1	0.1440	3537.2	2.8	0.843	6.41	0.47E-02	38.	T	.154	.000
					3114.4	9.8	0.742	6.41					
B 60H	2223.3	2115.5	3095.1	0.9524	23369.9	2.8	5.618	6.41	0.47E-02	38.	T	.154	.000
					20593.8	2.3	4.950	6.41					
61Fe	2245.2	2136.6	206.6	0.0640	1039.5	17.6	0.254	5.44	0.46E-02	9.	S	*	
					1374.4	20.6	0.335	6.41					
62x	2391.7	2276.0	311.5	0.1026	2849.5	12.3	0.764	9.99	0.42E-02	16.	S		
					2067.7	13.7	0.554	6.39					
63x	2414.0	2297.1	311.1	0.1022	3166.1	16.0	0.861	9.54	0.41E-02	24.	S		
					2063.8	13.8	0.561	6.39					

Table 4.16 (Continued) Fe CS

PEAK ANALYSIS PAGE 5

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE	
					AREA-G	ERR-G	INT-G	FWHM-C				
	KEV	CH NO	COUNTS	RATIO	CCUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
64Fe	2467.9	2348.0	165.6	0.0549	998.6	15.8	0.280	6.38	0.40E-02	13.	D	.507
					1097.5	24.7	0.308	6.38				
65Fe	2470.7	2350.7	140.7	0.0466	838.2	15.8	0.236	6.38	0.40E-02	13.	D	.507
					932.5	28.9	0.262	6.38				
66Fe	2524.6	2402.6	214.9	0.0754	1659.1	18.1	0.482	9.07	0.39E-02	14.	S	
					1421.7	18.9	0.413	6.37				
67Fe	2683.8	2552.5	210.4	0.0787	957.6	17.4	0.305	4.83	0.35E-02	9.	S	*
					1383.6	18.7	0.441	6.33				
68Fe	2721.8	2589.1	578.7	0.2203	3753.1	7.2	1.224	6.64	0.35E-02	16.	S	*
					3799.7	7.6	1.239	6.32				
69Fe	2834.2	2696.0	416.7	0.1629	2631.0	8.4	0.913	6.61	0.32E-02	13.	S	*
					2721.0	10.0	0.945	6.29				
70Fe	3103.1	2952.0	221.8	0.0978	957.8	16.1	0.403	4.59	0.27E-02	9.	S	*
					1423.2	16.8	0.599	6.18				
71Fe	3168.4	3014.4	161.7	0.0717	857.3	20.9	0.381	5.75	0.25E-02	11.	S	*
					1032.0	22.4	0.458	6.15				
72Fe	3195.7	3040.1	740.2	0.3253	4315.1	6.1	1.954	5.79	0.25E-02	17.	S	*
	DEP				4715.1	6.7	2.135	6.13				
73Fe	3269.0	3108.2	316.5	0.1541	2553.4	9.3	1.203	8.66	0.24E-02	16.	S	*
					2003.5	12.2	0.944	6.10				
74Fe	3356.6	3191.1	144.6	0.0746	700.7	22.0	0.345	4.89	0.23E-02	10.	S	*
					907.7	23.5	0.447	6.05				
75Fe	3385.2	3218.5	367.4	0.1939	2527.0	9.5	1.262	5.69	0.23E-02	17.	S	*
	DEP				2300.3	10.9	1.149	6.03				
76Fe	3413.5	3245.8	455.7	0.2360	2739.8	8.8	1.383	5.69	0.22E-02	17.	S	*
					2844.9	9.6	1.436	6.01				
77Fe	3437.1	3268.5	480.2	0.2565	3921.1	6.1	1.992	8.27	0.22E-02	17.	S	*
					2990.3	9.3	1.519	6.00				
78Fe	3668.4	3487.7	146.2	0.0870	433.9	25.9	0.257	3.18	0.19E-02	6.	S	
					886.8	22.7	0.525	5.84				
79Fe	3707.7	3524.8	257.4	0.1532	1825.3	11.1	1.124	7.16	0.18E-02	15.	S	*
	SEP				1553.0	15.1	0.957	5.81				

Table 4.16 (Continued) Fe CS

PEAK ANALYSIS PAGE 6

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
80Fe	3790.4	3602.0	363.1	0.2173	2919.0	8.1	1.932	7.78	0.17E-02	18.	S *
DEP					2166.6	13.2	1.434	5.75			
81Fe	3856.6	3664.4	289.3	0.1733	1419.2	11.0	0.966	5.13	0.17E-02	11.	S *
					1710.2	15.4	1.165	5.69			
82Fe	3897.3	3702.9	194.7	0.1246	1171.4	15.6	0.811	5.06	0.16E-02	14.	S *
SEP					1144.3	19.4	0.792	5.66			
83Fe	4216.2	4008.0	653.7	0.4770	4399.3	5.2	3.653	6.24	0.14E-02	19.	S *
					3642.6	18.8	3.025	5.37			

Table 4.16 (Continued) Fe CS

4.4.2 Iron Pair Spectrometer Results

Figure 4.6 shows the iron pair spectrometer spectrum of run 11071. Table 4.17 lists the GAMANL and GAMABC parameters for this run. Tables 4.18 and 4.19 present the GAMANL results and GAMABC results respectively. It is seen that 63 lines were analysed as being well resolved in the spectrum. Of these, 54 peaks are capture lines in iron, 7 peaks are marginal and tentatively assigned to iron, and 2 peaks are background peaks.

It is known that iron is present to some extent in the background, therefore the sample weight used in calculating the number of captures in the sample was corrected to include an effective equivalent amount of background iron. This amounted to 1.1 grams of equivalent background iron added to the total of 28.7 grams of the iron sample seen by the Ge(Li) detector. The number of captures in this equivalent amount of iron was less than 4% of the number of captures in the iron sample being studied.

From the spectrum of Figure 4.6 the continuum is seen to be quite low and flat over the entire spectrum energy range. The influence of the strong iron lines at 7631-7645 keV and at 6018 keV and 5920 keV on the continuum portion of the spectrum is seen in Figure 4.6. These iron results were used to obtain an estimate of the peak response function at these peak energies, as described in Section 3.6.2 of Chapter 3.

GAMABC was used to analyse the continuum of this data. Table 4.19 shows that the continuum contributes 18.5% to the observed fraction binding energy. The resolved peaks of all energies give 82.2% of the binding energy, with 79.7% from gamma peaks with energies greater than 1.5 MeV and 2.5% from gamma peaks with energies between 200 keV and 1.5 MeV. These combine to give a total of 100.6% of the binding energy.

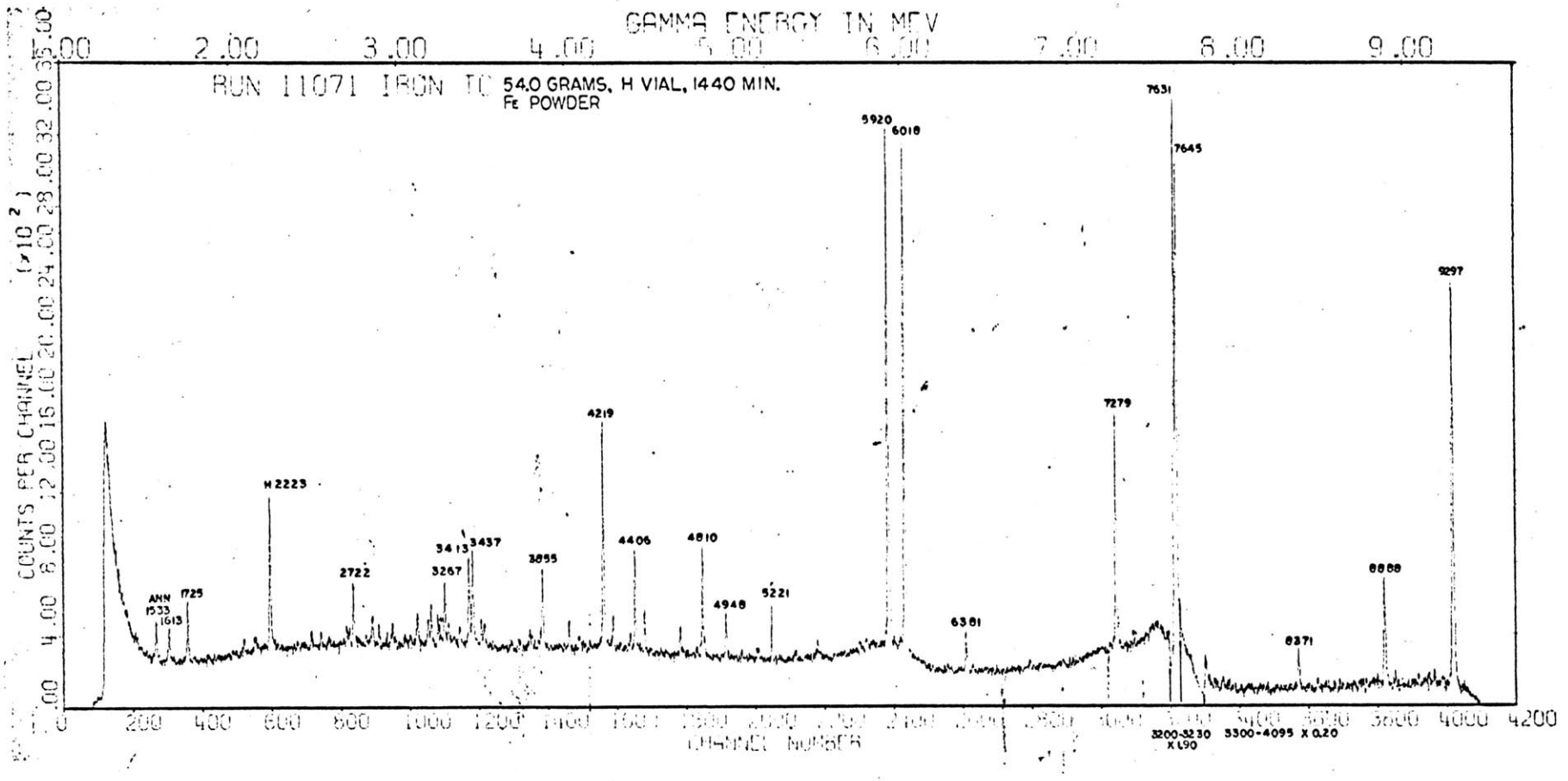

Figure 4.6 Iron Pair Spectrometer Spectrum 11071

```
PARAMETERS AND INPUT DATA FOR RUN 11071  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  217
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF PCINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   2.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  25.0
FIRST PEAK FWHM(KEV) FPS =  8.50 FWHM RANGE ERFW =  2.00
ENERGY PER CHANNEL NUMBER (KEV) = 2.066
CALIB1 E =2223.3 CNTR =  597 CORR = 596.4 FWHM =  8.43
CALIB2 E =7278.8 CNTR = 3045 CORR =3043.9 FWHM =  8.77
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.117E 12
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.927E-03
 0.915E-03 0.875E-03 0.813E-03 0.723E-03 0.637E-03
 0.550E-03 0.458E-03 0.369E-03 0.281E-03
NUMBER OF PEAKS ANALYSED = 79   J60323

GAMABC PEAK RESPONSE FUNCTION PARAMETERS
F2 = 0.00085 x AREA        F5 = 0.00160 x AREA
F3 = 0.00050 x AREA        F8 = 0.00576 x AREA
LOW CH = IMAX              MID CH = 900
W1 = 120 + 130(E - 2200)/4610 for E ≤ 6810 keV
W1 = 250 + 125(E - 6800)/ 450 for E > 6810 keV
W2 = 0.0004 x AREA + 2.0
W3 = 70
BAKFAC = 1.350   BINWIDTH = 20 Chs   RED = 1.0576
```

Table 4.17 Iron Pair Spectrometer Run 11071
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
B	1An	1532.9	267.4	185.4	0.6358	860.1	8.6	4.149	8.89	0.11E-03	12.	S	*
						840.0	9.8	4.053	8.23				
	2Fe	1613.5	304.9	180.2	0.6459	906.5	7.6	3.563	9.87	0.14E-03	11.	S	*
						814.2	9.9	3.201	8.21				
	3Fe	1725.7	358.1	334.5	1.2032	1495.5	5.4	4.669	7.54	0.17E-03	13.	S	*
						1506.2	6.5	4.702	8.18				
	4Fe	2065.1	520.7	78.6	0.2479	210.2	20.7	0.403	5.53	0.28E-03	5.	S	
						350.7	19.5	0.672	8.11				
	5Fe	2126.8	550.4	69.2	0.2066	218.1	21.3	0.390	8.09	0.30E-03	11.	D	.011
						308.4	22.1	0.551	8.09				
B	6H	2223.3	596.9	837.6	2.4014	4067.0	3.1	6.585	8.43	0.33E-03	19.	S	*
						3723.1	3.8	6.028	8.08				
	7Fe	2364.9	665.0	49.2	0.1564	174.0	27.4	0.247	7.49	0.38E-03	7.	S	*
						218.2	29.0	0.310	8.05				
	8Fe	2469.5	715.7	89.1	0.2529	295.2	20.8	0.384	6.33	0.41E-03	9.	S	*
						393.9	18.2	0.513	8.04				
	9Fe	2527.7	743.9	90.3	0.2656	358.0	17.0	0.445	8.27	0.43E-03	9.	S	*
						398.8	17.8	0.495	8.03				
	10Fe	2680.7	817.7	103.7	0.3040	523.4	13.2	0.579	8.00	0.49E-03	18.	D	.000
						456.8	15.9	0.505	8.00				
	11Fe	2697.0	825.6	97.5	0.2859	480.2	13.2	0.525	8.00	0.49E-03	18.	D	.000
						429.6	16.7	0.470	8.00				
	12Fe	2720.8	837.1	334.7	0.9537	1602.3	6.1	1.724	7.78	0.50E-03	15.	S	*
						1473.7	6.7	1.586	8.00				
	13Fe	2834.0	892.1	118.0	0.3049	525.5	13.5	0.525	9.00	0.54E-03	10.	S	*
						518.8	14.9	0.519	7.99				
	14Fe	2871.9	910.4	114.4	0.3288	439.3	13.1	0.429	7.17	0.55E-03	8.	S	*
						502.7	14.8	0.491	7.98				
	15Fe	2954.0	950.0	101.9	0.2920	437.0	16.5	0.407	7.98	0.58E-03	15.	D	.010
						447.2	16.2	0.417	7.98				

Table 4.18 Iron Pair Spectrometer Run 11071 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
16x	2992.3	968.6	49.0	0.1478	182.0	26.8	0.166	8.33	0.59E-03	7.	S *
					215.2	29.7	0.196	7.97			
17Fe	3103.5	1022.3	167.4	0.4633	860.9	9.7	0.740	11.31	0.62E-03	10.	S
					733.7	11.1	0.631	7.96			
18Fe	3167.7	1053.3	126.7	0.3398	603.8	13.4	0.503	8.94	0.64E-03	12.	S *
					554.8	13.9	0.462	7.96			
19Fe	3185.8	1062.0	185.9	0.4839	648.3	11.1	0.535	6.72	0.65E-03	10.	S *
					814.1	10.4	0.672	7.96			
20Fe	3225.2	1081.0	148.4	0.4150	551.8	11.6	0.447	6.98	0.66E-03	9.	S *
					649.9	12.1	0.527	7.96			
21Fe	3238.6	1087.6	86.4	0.2295	243.3	19.4	0.196	5.76	0.67E-03	6.	S *
					378.4	19.1	0.305	7.96			
22Fe	3267.6	1101.6	318.7	0.8160	1247.5	5.7	0.992	7.82	0.68E-03	9.	S *
					1395.2	7.1	1.109	7.95			
23x	3289.0	1112.1	98.3	0.2651	487.0	14.2	0.383	10.57	0.68E-03	8.	S
					430.1	17.1	0.339	7.95			
24Fe	3355.4	1144.3	96.2	0.2692	443.1	16.8	0.339	9.69	0.70E-03	9.	S
					421.0	17.2	0.322	7.95			
25Fe	3412.6	1171.9	451.1	1.1415	1970.0	4.6	1.473	8.39	0.72E-03	12.	S *
					1972.8	5.6	1.476	7.95			
26Fe	3436.2	1183.3	509.5	1.2686	2184.2	4.5	1.619	7.95	0.72E-03	13.	S *
					2228.1	5.2	1.651	7.95			
27Fe	3486.5	1207.7	130.0	0.3458	451.2	14.3	0.328	6.66	0.74E-03	9.	S *
					568.5	13.7	0.413	7.95			
28Fe	3505.2	1216.8	95.4	0.2587	462.7	20.6	0.334	9.91	0.74E-03	12.	S
					417.2	17.5	0.301	7.94			
29Fe	3778.2	1348.7	71.5	0.2055	283.7	19.7	0.186	8.77	0.82E-03	8.	S *
					312.3	21.8	0.205	7.94			
30Fe	3791.9	1355.3	71.4	0.2117	334.0	16.7	0.218	9.96	0.82E-03	8.	S *
					312.0	21.6	0.204	7.94			
31Fe	3854.1	1385.4	441.9	1.2537	2222.3	4.8	1.426	8.31	0.84E-03	16.	S *
					1931.9	5.6	1.240	7.94			

Table 4.18 (Continued) Fe PS

PEAK ANALYSIS PAGE 3

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	CCUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
32	Fe4C12.0	1461.9	147.3	0.4365	498.9	15.8	0.310	6.52	0.87E-03	10.	S	
					644.3	12.C	C.4CC	7.95				
33	Fe4070.4	1490.2	62.9	0.1872	245.2	24.4	0.151	7.27	0.87E-03	9.	S	*
					275.2	24.0	0.170	7.95				
34	Fe4219.1	1561.8	1248.1	3.4220	5682.3	2.2	3.449	8.02	0.88E-03	17.	S	*
					5467.9	3.0	3.319	7.96				
35	Fe4275.9	1589.4	187.8	0.5492	785.8	1C.6	0.474	7.76	0.89E-03	13.	S	*
					823.1	10.1	0.497	7.96				
36	Fe4379.2	1639.7	80.3	0.2401	255.1	19.5	0.153	6.52	0.90E-03	7.	S	*
					352.5	19.5	0.211	7.97				
37	Fe4406.2	1652.8	546.5	1.5821	2149.2	4.1	1.283	7.65	0.90E-03	12.	S	*
					2398.7	4.9	1.432	7.98				
38	Fe4462.2	1680.0	220.6	0.6908	911.7	7.0	0.542	8.51	0.90E-03	9.	S	*
					969.1	8.8	0.576	7.98				
39	Fe4675.2	1783.1	148.0	0.4783	534.C	11.2	0.312	7.03	0.92E-03	9.	S	*
					652.1	11.7	0.381	8.00				
40	x 4797.2	1842.3	72.7	0.2524	282.8	4.6	0.164	8.02	0.92E-03	19.	T	.000 .010
					321.1	2C.1	C.186	8.02				
41	Fe4810.5	1848.7	598.0	2.0752	2342.9	4.6	1.360	8.02	0.93E-03	19.	T	.000 .010
					2640.1	4.5	1.532	8.02				
42	x 4821.1	1853.9	87.5	0.3038	346.9	4.6	0.201	8.02	0.93E-03	19.	T	.000 .010
					386.5	17.3	0.224	8.02				
43	Fe4948.4 C	1915.5	237.4	0.8167	1105.7	7.2	0.638	8.49	0.93E-03	13.	S	*
					1050.7	8.2	0.607	8.04				
44	Fe5043.5	1961.7	57.5	0.2136	194.5	22.9	0.112	7.06	0.93E-03	7.	S	*
					254.8	24.C	0.147	8.06				
45	Fe5140.5	2008.8	58.5	0.2153	286.7	24.4	0.165	9.92	0.93E-03	10.	S	
					260.0	23.7	0.150	8.08				
46	Fe5221.3	2048.0	207.9	0.8019	497.0	9.7	C.287	5.06	0.93E-03	6.	S	
					925.5	8.8	0.534	8.09				
47	Fe5494.7	2180.3	63.8	0.2094	193.0	24.4	0.112	6.36	0.93E-03	7.	S	*
					285.9	22.9	0.166	8.15				

Table 4.18 (Continued) Fe PS

PEAK ANALYSIS PAGE 4

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
48	Fe5745.7	2302.2	66.0	0.2114	266.9	23.3	0.155	10.54	0.92E-03	8.	S	
					298.1	22.5	0.173	8.21				
49	Fe5786.2	2321.9	66.9	0.2101	427.7	19.3	0.249	13.21	0.92E-03	11.	S	
					302.5	22.4	0.176	8.22				
50	x 5902.6	2378.3	76.2	0.2165	361.9	1.5	0.211	8.25	0.92E-03	24.	D	.000
					346.3	20.7	0.202	8.25				
51	Fe5920.6	2387.0	2898.5	8.2311	13939.1	1.5	8.147	8.25	0.92E-03	24.	D	.000
					13165.6	1.9	7.695	8.25				
52	Fe6018.6	2434.6	2867.2	8.5681	13595.9	1.3	7.989	8.20	0.91E-03	24.	S	*
					13071.2	1.9	7.680	8.28				
53	Fe6380.5	2610.1	224.4	1.0446	1012.6	6.5	0.613	8.06	0.89E-03	12.	S	*
					1037.2	8.1	0.628	8.40				
54	x 6420.5	2629.4	51.3	0.2667	293.0	23.5	0.178	10.87	0.88E-03	12.	S	
					237.3	23.5	0.144	8.41				
55	Fe6760.8	2794.3	54.8	0.2571	212.5	22.6	0.135	7.83	0.85E-03	9.	S	*
					257.5	23.0	0.163	8.54				
56	x 6999.4	2909.7	63.5	0.2946	156.0	23.0	0.103	4.99	0.81E-03	5.	S	
					301.4	20.5	0.199	8.63				
57	x 7018.3	2918.9	43.6	0.1951	177.7	25.1	0.118	9.67	0.81E-03	8.	S	*
					207.4	28.3	0.138	8.64				
58	Fe7278.8	3045.4	1301.6	3.5340	6185.7	2.0	4.357	8.77	0.76E-03	16.	S	*
					6269.0	3.0	4.415	8.75				
59	Fe7631.7	3215.8	6021.1	14.7169	30407.2	0.6	23.307	8.92	0.70E-03	32.	D	.001
					29564.6	1.4	22.662	8.92				
60	Fe7646.0	3222.7	5447.9	13.3159	27279.0	0.6	20.983	8.92	0.70E-03	32.	D	.001
					26750.1	1.4	20.576	8.92				
61	Fe8371.1	3572.5	37.8	1.4529	154.0	13.7	0.144	7.92	0.57E-03	11.	S	*
					193.6	18.4	0.181	9.32				
62	Fe8888.2	3821.9	117.0	3.3408	602.6	5.5	0.677	9.79	0.48E-03	12.	S	*
					620.8	9.9	0.697	9.64				
63	Fe9297.4	4019.5	443.0	13.5069	2754.4	2.5	3.648	11.76	0.41E-03	22.	S	
					2417.5	5.3	3.202	9.92				

Table 4.18 (Continued) Fe PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	247	719.5	9613.9	21194.8	1500.0	2.76	35.0
					1613.5	3.56	7.6
					1725.7	4.67	5.4
		1270.6	-551.1			8.23	
2	368	-280.0	10198.5	21182.0	1750.0	-0.68	90.5
		575.8	-855.8			0.0	
3	489	1139.0	11311.8	25809.7	2000.0	2.04	24.2
					2065.1	0.40	20.7
					2126.8	0.39	21.3
		1485.7	-346.7			0.79	
4	610	1258.8	12309.4	26437.9	2250.0	1.79	22.4
					2364.9	0.25	27.4
					2469.5	0.38	20.8
		1569.7	-311.0			0.63	
5	731	313.3	13075.9	27298.4	2500.0	0.36	91.7
					2527.7	0.44	17.0
					2680.7	0.58	13.2
					2697.0	0.53	13.2
					2720.8	1.72	6.1
		1004.4	-691.1			3.27	
6	852	326.1	12893.7	27735.3	2750.0	0.32	88.5
					2834.0	0.53	13.5
					2871.9	0.43	13.1
					2954.0	0.41	16.5
					2992.3	0.17	26.8
		1219.9	-893.8			1.53	
7	973	355.2	12346.9	29358.0	3000.0	0.30	82.2
					3103.5	0.74	9.7
					3167.7	0.50	13.4
					3185.8	0.53	11.1
					3225.2	0.45	11.6
					3238.6	0.20	19.4
		1066.6	-711.5			2.42	
8	1094	1773.2	11966.2	31110.9	3250.0	1.36	16.8
					3267.6	0.99	5.7
					3289.0	0.38	14.2
					3355.4	0.34	16.8
					3412.6	1.47	4.6
					3436.2	1.62	4.5
					3486.5	0.33	14.3
		2073.4	-300.2			5.13	
9	1216	687.9	10860.6	27752.9	3500.0	0.47	40.8
					3505.2	0.33	20.6
		1109.5	-421.5			0.33	
10	1337	1364.8	10147.8	28446.7	3750.0	0.86	20.6

Table 4.19 Iron Pair Spectrometer Run 11071
GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 2

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
					3778.2	0.19	19.7
					3791.9	0.22	16.7
					3854.1	1.43	4.8
		1679.0	-314.3			1.83	
11	1458	717.4	9883.2	29077.7	4000.0	0.44	39.4
					4012.0	0.31	15.8
					4070.4	0.15	24.4
					4219.1	3.45	2.2
		1303.7	-586.3			3.91	
12	1579	2201.5	8568.3	28639.1	4250.0	1.32	12.6
					4275.9	0.47	10.6
					4379.2	0.15	19.5
					4406.2	1.28	4.1
					4462.2	0.54	7.0
		2342.2	-140.7			2.45	
13	1700	1184.0	7758.3	25974.6	4500.0	0.69	22.2
					4675.2	0.31	11.2
		1507.2	-323.2			0.31	
14	1821	617.9	7102.2	25207.6	4750.0	0.36	41.6
					4797.2	0.16	4.6
					4810.5	1.36	4.6
					4821.1	0.20	4.6
					4948.4	0.64	7.2
		1081.8	-463.9			2.36	
15	1942	534.3	6600.0	24016.7	5000.0	0.31	46.8
					5043.5	0.11	22.9
					5140.5	0.17	24.4
					5221.3	0.29	9.7
		972.3	-438.0			0.56	
16	2063	1938.3	5617.2	24770.4	5250.0	1.12	13.0
					5494.7	0.11	24.4
		2153.0	-214.7			0.11	
17	2184	1420.6	5283.8	27959.2	5500.0	-0.82	18.4
					5745.7	0.15	23.3
		1703.9	-283.3			0.15	
18	2305	1245.3	5090.8	34429.0	5750.0	0.73	22.8
					5786.2	0.25	19.3
					5902.6	0.21	1.5
					5920.6	8.15	1.5
		1540.0	-294.8			8.61	
19	2426	2272.6	3484.3	24169.0	6000.0	1.35	10.6
					6018.6	7.99	1.3
		2357.9	-85.3			7.99	
20	2547	1732.2	3214.3	18973.8	6250.0	1.05	12.4
					6380.5	0.61	6.5
					6420.5	0.18	23.5

Table 4.19 (Continued) Fe PS GAMAEC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 3

BIN NO	L CH NC	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
		1837.7	-105.6			0.79	
21	2668	2026.5	2872.8	18924.1	6500.0	1.26	10.6
		2116.3	-89.8			0.0	
22	2789	3256.2	2425.9	21144.4	6750.0	2.09	6.9
					6760.8	0.13	22.6
					6999.4	0.10	23.0
		3312.9	-56.8			0.24	
23	2910	1169.3	2739.1	29439.8	7000.0	0.79	22.0
					7018.3	0.12	25.1
		1500.7	-331.3			0.12	
24	3031	2733.0	2884.9	37500.4	7250.0	1.97	10.6
					7278.8	4.36	2.0
		2925.2	-192.2			4.36	
25	3152	3889.8	2393.5	38864.9	7500.0	2.98	7.6
					7631.7	23.31	0.6
					7646.0	20.98	0.6
		3980.4	-90.6			44.29	
26	3273	361.5	402.3	3525.6	7750.0	0.30	26.0
		661.4	-299.9			0.0	
27	3394	274.2	248.4	1470.7	8000.0	0.24	22.7
		355.3	-81.1			0.0	
28	3515	69.0	326.7	1570.1	8250.0	0.06	93.8
					8371.1	0.14	13.7
		233.0	-164.0			0.14	
29	3636	-50.9	280.8	1770.4	8500.0	-0.05	131.4
		160.7	-211.6			0.0	
30	3757	135.4	292.9	2159.2	8750.0	0.15	54.2
					8888.2	0.68	5.5
		313.2	-177.7			0.68	
31	3878	480.3	137.7	2291.8	9000.0	0.59	15.3
		518.5	-38.3			0.0	
32	3999	387.5	98.8	1103.0	9250.0	0.00	13.8
					9297.4	3.65	2.5
		421.2	-33.7			3.65	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 7848.00
UNRES = 18.7 -0.2 = 18.5%RES = 79.7%TOTAL = 98.1%
CS UNRES (EST)=0.0% CS RES=2.5% TOTAL ALL = 100.6%

Table 4.19 (Continued) Fe PS GAMABC Results

4.4.3 Iron Comparison

Table 4.20 shows a comparison of the result of this work with the published intensity data on iron. Basically only two publications list well resolved capture gamma results for natural iron: MITNE-85 (R-1) with which this work is related, and Groshev's (G-2) 1964 data. Since iron is used as a standard for the intensity values, in that the higher energy efficiency is determined from the intensity fit on the iron data, it is seen that more published data would be desirable. For example in comparing the combined results on the 7631-7645 keV iron doublet, the intensity values for these two lines combined are 44.3, 49.3 and 43.0 for this work, MITNE-85, and Groshev's data respectively. The difference of approximately 5.0 in the results means that the percent of the average binding energy seen will have an uncertainty of $\pm$ 5% just due to uncertainty of this data and to the strong energy weighting of this doublet. This uncertainty is, however, within the quoted accuracy of the results.

With this difference in the iron doublet results noted, it is seen that the majority of the lines listed in Table 4.17 agree quite well.

Table 4.20 Iron Comparison of Results

Strong Peaks Only, I > 0.45, Intensity, I, given in number of gamma rays of energy E emitted per 100 thermal neutron captures in the iron sample.

Present Work		MIT-NE-85 R-1	Nuclear Data Tables (ND-1) Groshev 64Gr36	
Energy keV	semi I	semi I	s Cp I	
9297.4	3.65	3.85	3.3	
8888.2	0.68	0.64	0.5	
7646.0	20.98	22.14	21.5	
7631.7	23.31	27.19	21.5	
7278.8	4.36	4.60	5.3	
6380.5	0.61	0.64	0.6	
6018.5	7.99	8.08	8.5	
5920.6	8.15	8.29	8.3	
4948.4	0.64	0.51	0.8	
4810.5	1.36	1.66	1.9	
4462.2	0.54	0.61	0.5	
4406.2	1.28	1.31	1.4	
4275.9	0.47	0.37	0.4	
4219.1	3.45	4.02	3.3	
3854.1	1.43	0.97	1.2	
3426.2	1.62	1.35	2.2	
3412.2	1.47	1.50	2.5	
3267.6	0.99	1.19	1.7	
3225.2	0.45	0.16	0.5	
3185.8	0.54	0.66	1.0	
3167.7	0.50	0.31	0.6	
3103.5	0.74	0.66	0.7	
2834.0	0.52	0.58	0.8	
2720.8	1.72	1.43	2.1	
2697.0	0.53	0.21	0.5	
2680.7	0.58	0.41	0.5	
2527.7	0.45	0.42	0.6	
1725.7	4.67	8.03	11	
1613.5	3.56	5.85	10	Greenwood 65Gr34 scin I
1603.1	0.73			2.5
1359.4	0.66	1.03		4.5
1260.8	2.19	2.38	4	4.5
1018.7	2.26	2.29		1.4
920.5	0.50	0.79		8.1
898.2	1.86	1.72	10	
811.0	1.00	0.88		
704.0	0.55			
692.5	6.13	4.91		
569.4	0.49	0.44		
411.5	1.03	0.69		1.9
366.2	1.53	1.47		
352.1	11.40	10.85		15.4
230.4	1.42	1.53		2.7

4.5 Comparison of Compton Suppression and Pair Spectrometer Results

There is a small region of overlap in the gamma energies between the Compton suppression data and pair spectrometer data. Table 4.21 compares the energies and intensities for the peaks in this overlapping region for the beryllium and iron results. It is seen that good agreement is obtained for both energy and intensity values, thus indicating that the run parameters used for both sets of data, as well as the efficiency values in the overlapping energy region, are consistent.

Table 4.21 Comparison of Compton Suppression and Pair Spectrometer Results for Iron and Beryllium Data.

	Compton Suppression			Pair Spectrometer		
Sample	Energy keV	$I_S^{(a)}$	$I_G^{(b)}$	Energy keV	$I_S^{(a)}$	$I_G^{(b)}$
Be	2588.8	21.55	21.72	2589.5	22.60	22.58
Be	3368.2	37.11	36.62	3366.9	34.47	35.03
Be	3444.3	9.99	12.11	3443.0	12.74	11.25
Fe	1613.3	5.72	5.58	1613.5	3.56	3.20
Fe	1725.6	6.58	6.47	1725.7	4.67	4.70
Fe	2067.6	0.28	0.44	2065.1	0.40	0.67
Fe	2129.5	0.50	0.59	2126.8	0.39	0.55
Fe	2467.9	0.28	0.31	2469.5	0.38	0.51
Fe	2524.6	0.48	0.41	2527.7	0.45	0.50
Fe	2683.8	0.31	0.44	2680.7	0.58	0.51
Fe	2721.8	1.22	1.24	2720.8	1.72	1.59
Fe	2834.2	0.91	0.95	2834.0	0.53	0.52
Fe	3103.1	0.40	0.60	3103.5	0.74	0.63
Fe	3168.4	0.38	0.46	3167.7	0.50	0.46
Fe	3269.0	1.20	0.94	3267.6	0.99	1.11
Fe	3356.6	0.34	0.45	3355.4	0.34	0.32
Fe	3413.5	1.38	1.44	3412.6	1.47	1.48
Fe	3437.1	1.99	1.52	3436.2	1.62	1.65
Fe	3856.6	0.97	1.17	3854.1	1.43	1.24
Fe	4216.2	3.65	3.03	4219.1	3.45	3.32

(a) Intensity value obtained by using summation method of area calculation, in number of photons/100 captures.

(b) Intensity value obtained by using Gaussian method of area calculation, in number of photons/100 captures.

5. NEODYMIUM RESULTS

5.1 Neodymium Sample

Table 5.1 lists the sample characteristics and run information for neodymium. It is seen that the sample consisted of neodymium oxide powder placed in a poly vial. The Westcott correction to the effective capture cross section is negligible for this sample. The nuclear data used to obtain the sample capture cross section of 51 barns, and average binding energy of 7480.0 keV were those listed in Nuclear Data, see ref. ND-2.

5.2 Neodymium Compton Suppression Results

Figure 5.1 shows the neodymium Compton suppression spectrum 11212 of 125 minutes duration. Tables 5.2 and 5.3 give the GAMANL parameters and GAMANL results respectively. The well resolved peaks are analysed and their energies and intensities are printed out in Table 5.3. It is seen that 57 peaks were analysed with 50 peaks printed out and 7 rejected because of the ECR criterion (error in peak area being too large). If the peak is from neodymium, it is so labeled in Table 5.3 in the first column. Background peaks, and marginal peaks (labeled with an x in column one) are also labeled. When the observed percent fraction of binding energy is calculated for the Compton suppression data (i.e., peaks with energies less than 1.5 MeV), the so labeled background peaks are not included in the calculation.

The marginal peaks are included in this calculation since they are tentatively assigned to the sample, and their contribution to the fraction seen is quite small.

TABLE 5.1 NEODYMIUM SAMPLE DATA AND RUN INFORMATION

Sample: Nd_2O_3 At. Wt.: 144.24

Wt: 7.24 gm Nd. Description: 8.41 gms Oxide in Poly

Holder: Al Vial 1/2" diam x 2". Vial Full.

Isotope:	Nd^{142}	Nd^{143}	Nd^{144}	Nd^{145}	Nd^{146}
Natural %:	27.11	12.17	23.85	8.30	17.22
Thermal Capture :	18b	335b	5.0b	52b	10b
Percent Captures in Natural Mixture:	9	77	2	8	3
Binding Energy of Product Nucleus: keV	6100	7830	5744	7561	5288

Effective Capture Cross Section: 51b

Westcott Correction: σ_c = 51b

Average Binding Energy for Sample: 7480.0 keV

Flux Depression Factor: F_1 = 0.85 $N_T\sigma_c$=1.568 cm^2 $\rho\bar{x}$ = 0.83 gm/cm^2

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	11212	11211
Computer Job No:	J50422	J61326
Average Thermal Flux: ϕ (n/cm^2sec)	$1.83 \times 10^{+8}$	$1.83 \times 10^{+8}$
Fraction of Sample Viewed by 1" Collimator:	1.00	1.00
Collimator Used:	1/2"	1/2"
Duration of Run (Min):	125	1500
Dead Time Corrected Run Time: (Min) t	102.5	1500
SANGLE	1.58×10^{-5}	1.58×10^{-5}
$FLUXT = F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	$1.50 \times 10^{+10}$	$2.20 \times 10^{+11}$

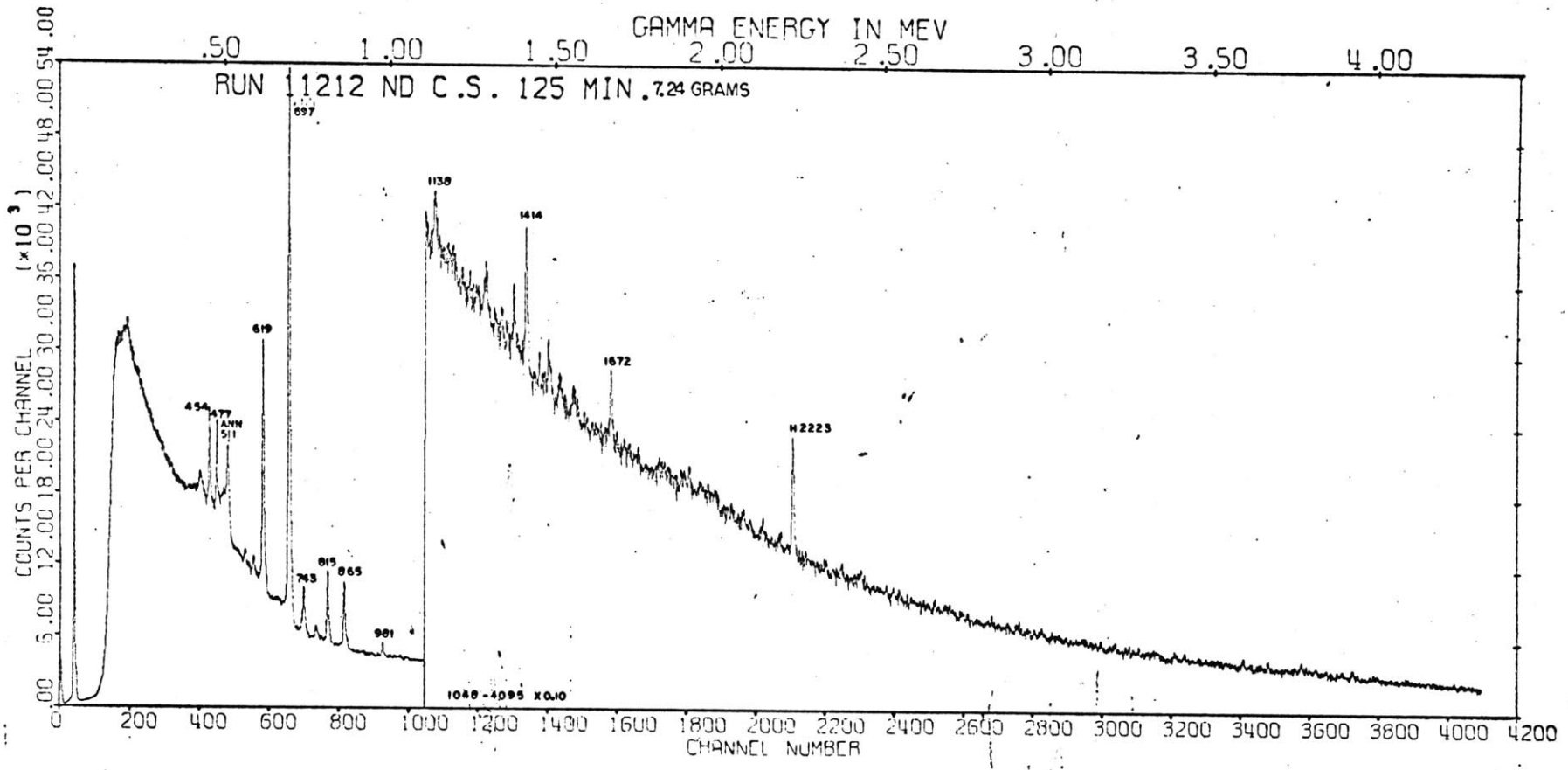

Figure 5.1 Neodymium Compton Suppression Spectrum 11212

```
PARAMETERS AND INPUT DATA FOR RUN 11212  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  184
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   2.5
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  6.25 FWHM RANGE ERFW =  2.25
ENERGY PER CHANNEL NUMBER (KEV) = 1.053
CALIB1 E = 511.0 CNTR =  482 CORR = 480.2 FWHM =  8.65
CALIB2 E =2223.3 CNTR = 2107 CORR =2106.8 FWHM =  6.56
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.150E 11
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.603E-01 0.322E-01 0.222E-01 0.163E-01 0.132E-01
 0.120E-01 0.100E-01 0.858E-02 0.748E-02 0.667E-02
 0.583E-02 0.512E-02 0.455E-02 0.404E-02 0.359E-02
 0.302E-02 0.273E-02 0.250E-02 0.206E-02 0.190E-02
 0.167E-02 0.145E-02 0.124E-02 0.110E-02 0.100E-02
 0.895E-03 0.787E-03 0.715E-03
NUMBER OF PEAKS ANALYSED = 57    J50422
```

Table 5.2 Neodymium Compton Suppression Run 11212 GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
1 Nd	201.0	193.6	1618.0	0.0532	9307.5	9.1	0.651	6.00	0.60E-01	17.	D	.015
					10756.7	8.0	0.753	6.00				
2 Nd	209.3	201.2	608.9	0.0200	3527.2	9.1	0.253	6.00	0.59E-01	17.	D	.015
					4048.1	20.7	0.291	6.00				
3 x	217.1	208.3	735.1	0.0254	2428.8	21.6	0.179	3.53	0.57E-01	7.	S	
					4885.4	16.8	0.359	5.99				
4 x	234.6	224.4	649.9	0.0236	2219.1	23.0	0.172	3.62	0.54E-01	7.	S	
					4317.3	18.5	0.335	5.99				
5 Nd	243.0	232.1	505.2	0.0189	2247.1	21.1	0.179	4.83	0.53E-01	8.	S	*
					3355.1	23.3	0.268	5.99				
6 Nd	310.9	294.9	719.6	0.0337	3576.2	13.1	0.354	5.45	0.42E-01	9.	S	*
					4770.4	14.8	0.472	5.98				
7 Nd	426.6	402.5	1385.9	0.0760	12911.5	7.0	1.773	10.77	0.31E-01	17.	S	
					9160.5	7.4	1.258	5.96				
8 Nd	454.5	428.6	6373.2	0.3707	39382.0	2.0	5.700	5.83	0.29E-01	19.	S	*
					42096.1	1.9	6.092	5.96				
NUMBER OF MAXIMA IN MULTIPLET = 4												
THE 3 STRONGEST PEAKS ARE ANALYSED AS A TRIPLET.												
9 Nd	477.1	449.8	3583.2	0.2376	34786.2	1.8	5.253	5.95	0.28E-01	54.	T	.000 .004
					23643.7	2.9	3.570	5.95				
10 x	502.5	473.8	3104.5	0.2059	30188.8	1.8	4.782	5.95	0.27E-01	54.	T	.000 .004
					20485.1	3.3	3.245	5.95				
B 11 Ann	511.0	481.8	7413.4	0.4917	71911.6	1.8	11.572	5.95	0.26E-01	54.	T	.000 .004
					48917.9	1.7	7.872	5.95				
12 Nd	564.5	532.1	1249.9	0.1036	7308.8	6.9	1.299	5.82	0.24E-01	14.	S	*
					8233.4	6.8	1.463	5.94				
13 Nd	576.5	543.4	294.8	0.0251	999.7	28.3	0.182	3.64	0.23E-01	7.	S	*
					1941.2	26.6	0.353	5.94				
14 Nd	590.3	556.4	1387.5	0.1231	8741.1	6.0	1.628	6.04	0.23E-01	15.	S	*
					9134.5	6.0	1.701	5.94				

Table 5.3 Neodymium Compton Suppression Run 11212 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
15Nd	618.9	583.4	20567.0	1.9942	135737.7	0.6	26.516	5.92	0.22E-01	24.	S *
					135302.7	0.8	26.431	5.93			
16Nd	671.1	632.8	264.2	0.0301	1160.0	23.5	0.246	4.73	0.20E-01	8.	S *
					1735.9	25.8	0.369	5.93			
17Nd	697.3	657.6	45588.5	5.6563	302868.8	0.3	66.987	5.93	0.19E-01	26.	S *
					299350.9	0.5	66.209	5.92			
18Nd	742.7	700.7	3908.2	0.6266	28832.9	2.6	6.833	5.92	0.18E-01	26.	D .000
					25632.7	2.1	6.074	5.92			
19Nd	755.2	712.5	276.5	0.0443	2002.5	2.6	0.483	5.92	0.17E-01	26.	D .000
					1813.5	21.1	0.438	5.92			
20Nd	779.3	735.5	1011.2	0.1706	6847.6	6.2	1.711	5.54	0.17E-01	17.	S *
					6627.2	6.2	1.656	5.91			
21Nd	795.6	750.9	256.8	0.0445	959.9	23.0	0.245	3.94	0.16E-01	8.	S *
					1682.7	21.8	0.430	5.91			
22Nd	814.7	769.0	5712.0	1.0072	35399.2	1.3	9.276	5.78	0.16E-01	17.	S *
					37404.8	1.6	9.801	5.91			
23Nd	864.9	816.7	5483.2	1.0944	40045.6	2.1	11.147	6.05	0.15E-01	39.	S *
					35865.9	1.6	9.983	5.90			
24Nd	981.2	926.9	1153.4	0.2657	6809.8	6.4	2.136	5.39	0.13E-01	21.	S *
					7524.7	5.0	2.360	5.88			
25Nd	1015.9	960.0	249.7	0.0587	868.0	19.8	0.278	3.68	0.13E-01	7.	S *
					1628.1	19.5	0.521	5.88			
26Nd	1034.5	977.7	198.2	0.0470	851.3	22.3	0.274	4.55	0.13E-01	8.	S *
					1291.7	24.2	0.416	5.88			
27x	1049.0	991.5	228.6	0.0564	1187.5	16.6	0.384	5.88	0.13E-01	16.	T .241 .241
					1489.4	20.8	0.482	5.88			
28Nd	1109.9	1048.9	185.3	0.0467	832.8	24.2	0.277	4.81	0.13E-01	9.	S *
					1205.9	25.1	0.401	5.87			
29Nd	1138.0	1075.4	415.8	0.1062	3130.9	12.7	1.055	7.27	0.12E-01	16.	S
					2704.0	11.7	0.911	5.86			
30Nd	1221.0	1154.2	161.5	0.0458	631.2	27.4	0.225	4.20	0.12E-01	8.	S *
					1048.6	27.1	0.374	5.85			

Table 5.3 (Continued) Nd CS

PEAK ANALYSIS PAGE 3

	NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S AREA-G COUNTS	ERR-S ERR-G PCSD	INT-S INT-G N/100C	FWHM-M FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
B	31A	1294.5	1224.2	215.5	0.0624	982.2	19.2	0.376	4.84	0.11E-01	9.	S *
						1396.8	20.4	0.534	5.85			
	32Nd	1341.3	1268.7	265.7	0.0856	1381.9	16.3	0.552	5.19	0.11E-01	12.	S *
						1720.4	16.0	0.687	5.84			
	33Nd	1356.4	1282.9	158.7	0.0518	854.8	24.4	0.346	5.71	0.10E-01	11.	S *
						1027.7	25.9	0.416	5.84			
	34Nd	1377.1	1302.5	481.4	0.1552	2273.2	9.4	0.937	4.60	0.10E-01	11.	S *
						3115.2	9.4	1.284	5.84			
	35Nd	1414.1	1337.6	1179.9	0.4076	8418.7	4.1	3.581	5.91	0.99E-02	20.	S *
						7630.1	4.4	3.245	5.83			
	36x	1453.3	1374.8	184.9	0.0682	604.8	22.7	0.265	3.46	0.96E-02	7.	S *
						1194.6	21.2	0.524	5.83			
	37Nd	1482.2	1402.3	396.6	0.1534	2511.0	10.0	1.126	5.82	0.94E-02	22.	D .038
						2561.5	10.4	1.149	5.82			
	38Nd	1487.9	1407.7	285.4	0.1104	1814.2	10.0	0.817	5.82	0.93E-02	22.	D .038
						1843.3	13.9	0.830	5.82			
	39Nd	1516.3	1434.7	179.9	0.0690	1320.0	20.4	0.608	7.82	0.91E-02	13.	S
						1161.0	21.4	0.535	5.82			
	40Nd	1672.5	1583.3	552.4	0.2389	3138.3	7.2	1.620	5.34	0.81E-02	14.	S *
						3555.2	7.5	1.835	5.81			
	41Nd	1866.6	1767.7	126.7	0.0675	417.0	27.4	0.243	3.51	0.72E-02	7.	S *
						812.7	25.7	0.474	5.79			
	42Nd	1910.1	1809.0	163.8	0.0872	890.7	18.4	0.532	5.82	0.70E-02	11.	S *
						1050.0	20.3	0.628	5.78			
	43Nd	1967.1	1863.1	137.2	0.0773	518.1	23.8	0.320	3.99	0.68E-02	8.	S *
						879.0	23.3	0.544	5.78			
	44Nd	2133.6	2021.9	133.1	0.0913	799.3	20.7	0.552	5.32	0.61E-02	13.	S *
						850.5	22.1	0.587	5.76			
B	45H	2223.3	2107.3	933.1	0.7089	6686.7	3.8	4.900	6.56	0.57E-02	22.	S *
						5954.5	4.5	4.363	5.76			
	46Nd	2371.4	2248.7	99.7	0.0888	767.7	21.3	0.619	7.51	0.52E-02	15.	S *
						635.1	25.8	0.512	5.74			

Table 5.3 (Continued) Nd CS

PEAK ANALYSIS PAGE 4

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
47Nd	2527.9	2397.6	91.3	0.0968	797.2	24.5	0.706	9.41	0.47E-02	16.	S
					580.1	26.1	0.514	5.73			
48x	3668.5	3479.7	77.6	0.2118	462.3	16.0	0.839	6.62	0.23E-02	11.	S *
					488.7	29.8	0.887	5.68			
49x	3770.4	3575.5	67.9	0.1796	283.8	20.5	0.566	4.42	0.21E-02	8.	S *
					427.9	34.3	0.854	5.68			
50x	3927.4	3723.4	60.5	0.1968	525.5	21.3	1.124	9.99	0.20E-02	16.	S
					380.8	39.8	0.815	5.68			

Table 5.3 (Continued) Nd CS

5.3 Neodymium Pair Spectrometer Results

Figure 5.2 shows the neodymium pair spectrometer spectrum, run 11211. The spectrum shows the gamma peaks well resolved at the high energy end of the data, i.e., gamma energies greater than 4.5 MeV. Below 4.5 MeV gamma energy, the peaks are observed to decrease in height and blend together to form a continuous region.

Table 5.4 gives the GAMANL and GAMABC parameters for run 11211. Tables 5.5 and 5.6 present the GAMANL results and GAMABC results respectively. In the gamma energy range from 1.5 MeV to 5.0 MeV many small peaks are analysed. The GAMANL code performed analysis upon 107 peaks, of these: 91 were due to captures in the Nd sample, 6 were marginal peaks and tentatively assigned to Nd, 9 were background peaks, and 1 peak was rejected because of the multiplet criterion.

Table 5.6 presents the results of the GAMABC continuum analysis. The continuum intensity reaches a maximum at a gamma energy of about 2.25 MeV. The fraction of average binding energy observed is 91.0% total. This is broken into: 41.7% being due to the resolved gamma peaks of both the Compton suppression and pair spectrometer data for energy above 200 keV, the Compton suppression lower energy cutoff; 47.1% being due to the unresolved continuum of energy greater than 1.5 MeV; and 2.2% as estimated being due to the continuum from unresolved capture gammas of energy below 1.5 MeV.

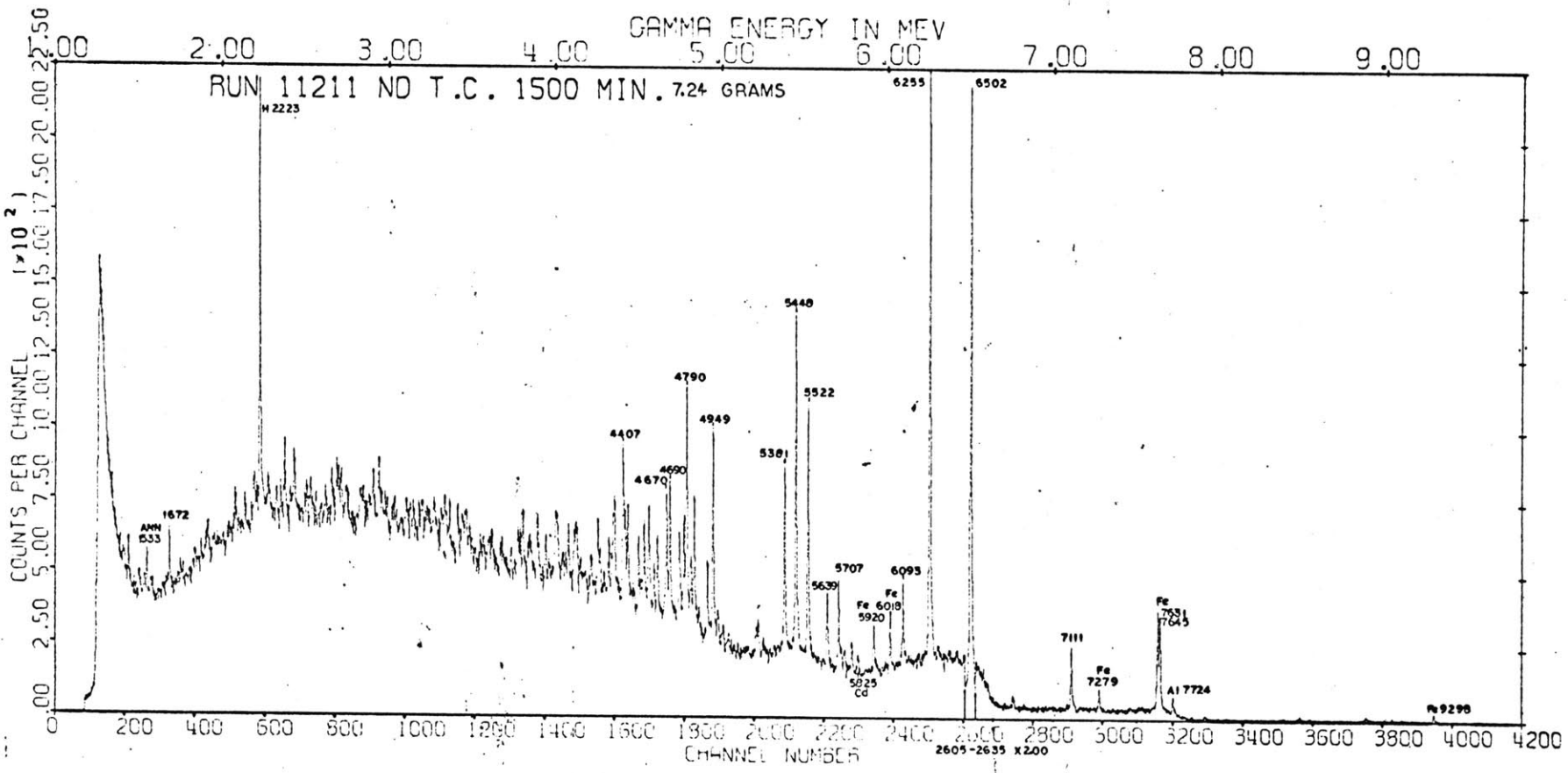

Figure 5.2 Neodymium Pair Spectrometer Spectrum 11211

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PARAMETERS AND INPUT DATA FOR RUN 11211  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  226
BACKGROUND CRITERION BCR * SQRT(BK) BCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  8.00 FWHM RANGE ERFW =  4.00
ENERGY PER CHANNEL NUMBER (KEV) = 2.104
CALIB1 E =2223.3 CNTR =  586 CORR = 585.6 FWHM =  7.98
CALIB2 E =7278.8 CNTR = 2990 CORR =2988.6 FWHM =  7.50
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.220E 12
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.927E-03
 0.915E-03 0.875E-03 0.813E-03 0.723E-03 0.637E-03
 0.550E-03 0.458E-03 0.369E-03 0.281E-03
NUMBER OF PEAKS ANALYSED =107   J61326

GAMABC PEAK RESPONSE FUNCTION PARAMETERS
F2 = 0.00085 x AREA      F5 = 0.0014 x AREA
F3 = 0.00040 x AREA      F8 = 0.0042 x AREA
LOW CH = IMAX            MID CH = 900
W1 = 120 + 130 (E - 2200)/4610 for E ≤ 6810 keV
W1 = 250 + 125 (E - 6800)/ 450 for E > 6810 keV
W2 = 0.0004 x AREA + 2.0
W3 = 70
BAKFAC = 1.350   BIN WIDTH = 10 Chs   RED = 1.042
```

Table 5.4 Neodymium Pair Spectrometer Run 11211
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S / AREA-G	ERR-S / ERR-G	INT-S / INT-G	FWHM-M / FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1x	1463.8	232.1	72.7	0.1767	149.7	24.3	0.468	4.39	0.92E-04	4.	S *
					299.4	22.9	0.936	7.37			
2Nd	1481.9	240.1	94.4	0.2254	485.5	19.4	1.445	10.86	0.96E-04	11.	S
					388.6	18.5	1.157	7.38			
B 3An	1532.8	262.8	144.2	0.3289	516.0	12.4	1.330	7.51	0.11E-03	8.	S *
					594.1	13.3	1.531	7.38			
4Nd	1672.3	326.9	184.6	0.4031	652.7	11.0	1.207	6.81	0.16E-03	9.	S *
					762.5	11.1	1.410	7.40			
5Nd	1910.0	438.1	88.3	0.1470	197.2	25.9	0.245	4.83	0.23E-03	5.	S *
					366.1	22.3	0.455	7.43			
6Nd	2072.1	514.7	111.1	0.1633	285.5	19.2	0.290	5.32	0.28E-03	5.	S *
					462.2	19.1	0.469	7.45			
7Nd	2130.6	542.2	102.5	0.1549	240.0	22.4	0.228	4.87	0.30E-03	5.	S *
					426.8	20.3	0.406	7.46			
8Nd	2185.8	568.3	87.9	0.1243	515.4	16.4	0.463	7.47	0.32E-03	16.	D .415
					366.6	23.9	0.329	7.47			
9Nd	2188.4	569.6	94.6	0.1337	524.1	16.4	0.469	7.47	0.32E-03	16.	D .415
					394.5	22.3	0.353	7.47			
B 10H	2223.3	586.1	1446.1	1.9717	6448.5	2.8	5.577	7.98	0.33E-03	19.	S *
					6034.8	3.0	5.219	7.48			
11Nd	2323.1	633.2	104.3	0.1498	455.1	20.5	0.358	8.43	0.36E-03	10.	S *
					436.3	20.3	0.344	7.49			
12Nd	2347.7	644.8	90.6	0.1275	236.3	26.7	0.182	5.41	0.37E-03	6.	S *
					379.0	23.3	0.292	7.50			
13Nd	2372.4	656.5	196.9	0.2784	924.6	11.9	0.697	8.73	0.38E-03	12.	S *
					824.3	11.9	0.621	7.50			
14Nd	2404.9	671.9	114.8	0.1665	643.6	13.2	0.472	7.51	0.39E-03	23.	D .000
					481.2	18.6	0.353	7.51			
15Nd	2428.5	683.1	202.2	0.2933	1130.4	13.2	0.813	7.51	0.40E-03	23.	D .000
					847.6	11.6	0.609	7.51			

Table 5.5 Neodymium Pair Spectrometer Run 11211 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK. CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE	
					AREA-G	ERR-G	INT-G	FWHM-C				
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
16Nd	2504.4	719.3	106.8	0.1557	503.5	15.6	0.341	10.40	0.42E-03	8.	S *	
					448.6	19.8	0.303	7.52				
17Nd	2527.2	730.2	138.2	0.1988	615.0	14.1	0.408	7.34	0.43E-03	9.	S *	
					580.5	15.9	0.385	7.53				
18Nd	2558.5	745.1	118.7	0.1773	384.5	18.1	0.249	6.72	0.44E-03	7.	S *	
					499.0	17.9	0.323	7.53				
19Nd	2654.0	790.3	123.0	0.1703	383.3	18.9	0.231	6.43	0.48E-03	7.	S *	
					518.3	17.9	0.312	7.55				
20Nd	2685.3	805.1	125.6	0.1706	480.2	15.2	0.283	7.56	0.49E-03	13.	D .005	
					529.6	17.7	0.312	7.56				
21Nd	2695.9	810.1	124.0	0.1686	473.8	15.2	0.277	7.56	0.49E-03	13.	D .005	
					523.1	17.8	0.306	7.56				
22Nd	2711.4	817.4	108.0	0.1449	422.0	19.2	0.244	8.22	0.50E-03	8.	S *	
					455.6	20.3	0.264	7.56				
23Nd	2904.0	909.1	136.9	0.1863	416.5	17.5	0.213	6.32	0.56E-03	7.	S *	
					580.3	16.4	0.297	7.60				
24Nd	2936.1	924.3	192.1	0.2696	746.5	12.8	0.375	7.28	0.57E-03	10.	S *	
					815.4	12.2	0.410	7.60				
25Nd	2989.1	949.4	99.9	0.1495	334.8	18.6	0.163	7.11	0.59E-03	6.	S *	
					424.4	20.8	0.207	7.61				
26Nd	3100.9	1002.6	106.7	0.1656	620.3	17.4	0.285	14.24	0.62E-03	10.	S	
					454.6	19.4	0.209	7.64				
27Nd	3125.4	1014.2	129.8	0.2042	438.0	15.6	0.199	6.47	0.63E-03	7.	S *	
					553.7	16.3	0.251	7.64				
28Nd	3177.7	1038.9	151.3	0.2485	598.1	11.6	0.265	7.65	0.65E-03	17.	T .000 .152	
					646.7	14.1	0.286	7.65				
29Nd	3195.1	1047.2	108.5	0.1781	431.3	11.6	0.189	7.65	0.65E-03	17.	T .000 .152	
					463.6	18.7	0.203	7.65				
30Nd	3200.1	1049.5	112.4	0.1846	422.6	11.6	0.185	7.65	0.66E-03	17.	T .000 .152	
					480.4	18.1	0.210	7.65				
31Nd	3269.0	1082.2	99.6	0.1508	450.1	23.3	0.191	8.04	0.68E-03	12.	S *	
					426.4	20.8	0.181	7.67				

Table 5.5 (Continued) Nd PS

PEAK ANALYSIS PAGE 3

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE		
					AREA-G	ERR-G	INT-G	FWHM-C					
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN			
NUMBER OF MAXIMA IN MULTIPLET = 4													
THE 3 STRONGEST PEAKS ARE ANALYSED AS A TRIPLET.													
32Nd	3312.1	1102.8	129.5	0.2148	653.2	10.7	0.272	7.68	0.69E-03	21.	T	.000	.006
					555.6	16.0	0.231	7.68					
33Nd	3333.5	1113.0	150.3	0.2492	762.5	10.7	0.315	7.68	0.70E-03	21.	T	.000	.006
					644.6	14.1	0.266	7.68					
34Nd	3343.4	1117.7	94.0	0.1558	469.2	10.7	0.193	7.68	0.70E-03	21.	T	.000	.006
					403.1	21.1	0.166	7.68					
35Nd	3363.0	1127.1	121.4	0.1939	356.1	17.0	0.145	6.17	0.70E-03	6.	S	*	
					521.1	17.1	0.212	7.69					
36Nd	3410.8	1149.8	186.0	0.3413	782.8	10.8	0.313	7.70	0.72E-03	12.	D	.155	
					799.8	11.5	0.320	7.70					
37Nd	3417.3	1152.9	72.2	0.1324	306.2	10.8	0.122	7.70	0.72E-03	12.	D	.155	
					310.3	25.6	0.124	7.70					
38Nd	3438.6	1163.0	132.6	0.2286	714.2	12.2	0.282	7.71	0.73E-03	23.	T	.000	.156
					570.9	15.5	0.226	7.71					
39Nd	3456.3	1171.4	100.8	0.1737	530.2	12.2	0.208	7.71	0.73E-03	23.	T	.000	.156
					433.8	19.6	0.170	7.71					
40Nd	3462.3	1174.3	95.1	0.1640	512.7	12.2	0.201	7.71	0.73E-03	23.	T	.000	.156
					409.4	20.6	0.160	7.71					
41Nd	3546.8	1214.4	101.6	0.1945	392.3	17.5	0.149	5.72	0.76E-03	8.	S	*	
					438.6	18.7	0.166	7.73					
42Nd	3733.2	1302.9	99.4	0.2005	407.2	17.9	0.144	8.59	0.81E-03	9.	S	*	
					431.5	18.7	0.153	7.78					
43Nd	3774.2	1322.4	90.8	0.1666	401.0	17.4	0.140	9.88	0.82E-03	8.	S	*	
					394.6	20.9	0.138	7.79					
44Nd	3788.9	1329.3	87.8	0.1627	327.5	21.1	0.114	8.02	0.82E-03	8.	S	*	
					381.8	21.5	0.133	7.79					
45Nd	3803.9	1336.4	206.7	0.3928	912.5	7.9	0.317	9.60	0.83E-03	8.	S	*	
					899.1	10.5	0.312	7.79					
46Nd	3833.7	1350.6	139.7	0.2911	558.5	9.1	0.192	7.80	0.83E-03	17.	T	.040	.040
					608.7	13.9	0.210	7.80					

Table 5.5 (Continued) Nd PS

PEAK ANALYSIS PAGE 4

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE		
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN			
47Nd	3843.4	1355.2	153.0	0.3188	628.8	9.1	0.216	7.80	0.83E-03	17.	T	.040	.040
					666.7	12.9	0.229	7.80					
48Nd	3852.2	1359.4	114.5	0.2385	466.7	9.1	0.160	7.80	0.84E-03	17.	T	.040	.040
					498.7	16.4	0.171	7.80					
49Nd	3892.1	1378.3	217.3	0.4323	1233.5	8.2	0.419	8.95	0.84E-03	13.	S	*	
					948.1	9.9	0.322	7.82					
50Nd	3942.2	1402.2	144.3	0.2992	579.3	12.7	0.195	7.55	0.85E-03	9.	S	*	
					630.7	13.6	0.212	7.83					
51Nd	4002.5	1430.8	186.1	0.3645	1014.9	8.1	0.337	7.85	0.86E-03	17.	D	.166	
					815.1	11.3	0.270	7.85					
52Nd	4008.8	1433.8	167.8	0.3286	914.4	8.1	0.303	7.85	0.86E-03	17.	D	.166	
					734.9	12.2	0.244	7.85					
53Nd	4077.5	1466.4	171.8	0.3442	766.0	9.9	0.252	9.56	0.87E-03	9.	S	*	
					754.2	11.9	0.248	7.86					
54Nd	4113.1	1483.4	212.5	0.4792	853.1	6.0	0.280	7.88	0.88E-03	18.	T	.007	.042
					934.4	9.8	0.306	7.88					
55Nd	4122.3	1487.8	221.1	0.4985	906.0	6.0	0.297	7.88	0.88E-03	18.	T	.007	.042
					971.8	9.5	0.318	7.88					
56Nd	4130.2	1491.5	204.2	0.4605	814.1	6.0	0.266	7.88	0.88E-03	18.	T	.007	.042
					897.9	10.1	0.294	7.88					
57Nd	4214.5	1531.3	108.7	0.2400	572.3	12.4	0.186	11.43	0.88E-03	9.	S	*	
					479.2	16.8	0.155	7.90					
58Nd	4257.1	1551.5	264.4	0.6057	1137.5	7.4	0.367	7.91	0.89E-03	16.	D	.000	
					1167.7	8.3	0.377	7.91					
59Nd	4270.4	1557.8	162.5	0.3722	722.2	7.4	0.233	7.91	0.89E-03	16.	D	.000	
					717.6	12.0	0.232	7.91					
60Nd	4323.4	1583.1	154.3	0.3444	585.8	13.1	0.188	7.05	0.89E-03	10.	S	*	
					682.9	12.6	0.219	7.93					
61Nd	4351.2	1596.4	192.7	0.4142	951.1	6.9	0.305	7.94	0.90E-03	18.	D	.173	
					853.8	10.7	0.273	7.94					
62Nd	4356.3	1598.8	273.7	0.5884	1343.4	6.9	0.430	7.94	0.90E-03	18.	D	.173	
					1212.7	8.2	0.388	7.94					

Table 5.5 (Continued) Nd PS

PEAK ANALYSIS PAGE 5

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
63Nd	4407.1	1623.1	492.0	1.1872	2376.1	4.1	0.758	7.96	0.90E-03	27.	T	.000 .000
					2185.3	5.4	0.697	7.96				
64Nd	4421.0	1629.8	307.7	0.7426	1475.3	4.1	0.470	7.96	0.90E-03	27.	T	.000 .000
					1366.8	7.4	0.435	7.96				
65Nd	4436.6	1637.2	317.1	0.7651	1527.7	4.1	0.486	7.96	0.90E-03	27.	T	.000 .000
					1408.3	7.2	0.448	7.96				
66Nd	4501.2	1668.0	245.8	0.6182	1141.1	7.5	0.361	7.98	0.91E-03	28.	T	.000 .000
					1095.2	8.6	0.347	7.98				
67Nd	4515.2	1674.7	91.9	0.2312	420.0	7.5	0.133	7.98	0.91E-03	28.	T	.000 .000
					409.5	18.5	0.129	7.98				
68Nd	4534.8	1684.0	282.6	0.7109	1312.3	7.5	0.414	7.98	0.91E-03	28.	T	.000 .000
					1259.3	7.7	0.397	7.98				
69Nd	4563.5	1697.6	339.8	0.8353	1603.5	5.6	0.505	8.71	0.91E-03	12.	S	*
					1516.7	6.8	0.477	8.00				
70Nd	4594.9	1712.5	162.7	0.4223	548.0	11.1	0.172	7.07	0.91E-03	8.	S	*
					727.2	11.5	0.228	8.01				
71Nd	4615.0	1722.1	277.4	0.7264	1101.8	7.2	0.346	7.56	0.91E-03	11.	S	*
					1240.6	7.8	0.389	8.01				
72Nd	4669.8	1748.2	445.3	1.2011	2185.9	4.8	0.683	8.03	0.92E-03	29.	D	.000
					1996.1	5.6	0.624	8.03				
73Nd	4690.3	1757.9	487.1	1.3141	2396.1	4.8	0.748	8.03	0.92E-03	29.	D	.000
					2183.9	5.3	0.681	8.03				
74Nd	4747.1	1784.9	267.4	0.7020	1269.4	6.7	0.395	8.97	0.92E-03	12.	S	*
					1201.8	8.0	0.374	8.05				
75Nd	4774.4	1797.9	316.8	0.8259	1368.4	3.2	0.425	8.06	0.92E-03	18.	D	.000
					1425.8	7.1	0.443	8.06				
76Nd	4790.6	1805.6	800.4	2.0863	3367.6	3.2	1.045	8.06	0.92E-03	18.	D	.000
					3601.7	3.9	1.117	8.06				
77Nd	4817.4	1818.4	190.5	0.4847	700.7	9.7	0.217	6.56	0.93E-03	9.	S	*
					858.3	10.3	0.266	8.07				
78Nd	4836.0	1827.2	383.3	0.9902	1641.7	5.1	0.508	8.39	0.93E-03	11.	S	*
					1728.1	6.3	0.535	8.08				

Table 5.5 (Continued) Nd PS

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE	
					AREA-G	ERR-G	INT-G	FWHM-C				
	KEV	CH NC	COUNTS	RATIO	CCUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
79Nd	4915.8	1865.2	239.8	0.7612	813.8	7.7	0.251	6.79	0.93E-03	9.	S	*
					1084.6	8.3	0.335	8.10				
80Nd	4949.3	1881.1	720.8	2.3184	3168.8	3.2	0.977	7.90	0.93E-03	15.	S	*
					3264.1	4.1	1.006	8.11				
81x	4980.7	1896.0	96.0	0.3416	530.8	14.8	0.164	12.06	0.93E-03	11.	S	
					435.2	15.9	0.134	8.12				
82Nd	5100.3	1953.0	53.6	0.2488	175.6	27.2	0.054	5.71	0.93E-03	9.	S	*
					244.1	23.5	0.075	8.16				
83Nd	5211.3	2006.0	96.6	0.4370	519.2	10.2	0.160	8.20	0.93E-03	18.	D	.010
					442.2	14.8	0.136	8.20				
84Nd	5222.7	2011.4	104.1	0.4708	546.6	10.2	0.168	8.20	0.93E-03	18.	D	.010
					476.4	14.0	0.147	8.20				
85Nd	5380.8	2086.7	636.4	2.4302	2918.9	3.4	0.901	8.34	0.93E-03	16.	S	*
					2930.8	4.3	0.905	8.25				
86Nd	5448.4	2118.9	1131.5	4.4527	5363.6	2.3	1.657	7.92	0.93E-03	20.	S	*
					5225.1	3.1	1.614	8.27				
87Nd	5522.0	2153.8	846.0	3.7044	3972.5	2.5	1.228	7.95	0.93E-03	16.	S	*
					3918.6	3.7	1.212	8.30				
88Nd	5638.6	2209.3	257.3	1.3301	1240.6	5.8	0.384	8.51	0.93E-03	14.	S	*
					1197.8	7.3	0.371	8.34				
89Nd	5706.8	2241.9	328.1	1.8314	1456.5	6.5	0.451	8.37	0.93E-03	21.	D	.000
					1532.2	6.2	0.475	8.37				
90Nd	5723.5	2249.8	72.6	0.4054	321.2	6.5	0.100	8.37	0.93E-03	21.	D	.000
					339.2	17.4	0.105	8.37				
91Nd	5744.2	2259.6	66.9	0.3863	397.5	15.6	0.123	12.94	0.92E-03	11.	S	
					312.7	18.4	0.097	8.38				
92x	5787.5	2280.2	98.2	0.5642	482.0	11.0	0.150	10.05	0.92E-03	11.	S	*
					459.9	13.8	0.143	8.39				
93x	5822.3	2296.8	66.0	0.4042	354.3	14.3	0.110	10.95	0.92E-03	11.	S	*
					309.7	18.2	0.096	8.40				
B 94Fe	5919.6	2343.2	156.1	0.8925	630.1	7.2	0.197	8.52	0.92E-03	8.	S	*
					735.4	9.9	0.230	8.44				

Table 5.5 (Continued) Nd PS

PEAK ANALYSIS PAGE 7

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NC	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
B 95Fe	6017.8	2389.9	122.1	0.6528	538.9	10.3	0.169	8.85	0.91E-03	11.	S *
					577.7	12.0	0.181	8.47			
96Nd	6093.8	2426.1	257.4	1.2131	1051.8	6.6	0.332	7.29	0.91E-03	13.	S *
					1221.5	7.4	0.385	8.50			
97Nd	6255.3	2503.0	1981.4	8.8340	9977.7	1.4	3.189	8.53	0.90E-03	22.	S *
					9471.1	2.3	3.027	8.56			
98Nd	6501.7	2620.3	4277.0	18.6765	22723.6	0.9	7.448	8.93	0.87E-03	27.	S *
					20672.4	1.6	6.776	8.66			
99x	6581.3	2658.3	45.7	0.3592	139.0	22.3	0.046	6.27	0.87E-03	7.	S *
					221.6	22.6	0.073	8.69			
100x	6758.8	2742.5	41.6	0.8757	202.3	13.2	0.069	10.99	0.85E-03	10.	S *
					203.7	19.0	0.069	8.76			
101Nd	7111.0	2909.9	212.2	4.1292	967.0	4.8	0.350	8.29	0.79E-03	16.	S *
					1055.6	7.2	0.382	8.91			
B102Fe	7278.8	2989.8	73.6	1.5381	262.4	9.0	0.099	7.50	0.76E-03	7.	S *
					369.1	13.3	0.139	8.98			
B103Fe	7631.0	3157.0	332.3	6.8506	1626.8	2.5	0.666	9.14	0.70E-03	22.	D .005
					1696.0	5.7	0.694	9.14			
B104Fe	7644.5	3163.5	319.8	6.5948	1527.1	2.5	0.627	9.14	0.70E-03	22.	D .005
					1632.7	5.8	0.670	9.14			
B105Al	7723.2	3200.9	50.7	1.3942	203.0	11.2	0.085	8.43	0.68E-03	9.	S *
					260.0	16.1	0.109	9.18			
B106Fe	9297.7	3946.5	26.1	3.9340	126.0	9.7	0.089	9.38	0.41E-03	11.	S *
					145.5	20.5	0.103	9.98			

Table 5.5 (Continued) Nd PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR CCUNTS	BKGND AR CCUNTS	LEC AR CCUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	243	1641.9	8860.2	40949.4	1500.0	3.36	19.5
					1672.3	1.21	11.0
		2079.1	-437.2			1.21	
2	362	8564.1	9415.3	46777.9	1750.0	11.18	4.1
					1910.0	0.25	25.9
		8566.4	-2.3			0.25	
3	480	15511.1	10507.0	53505.9	2000.0	14.84	2.4
					2072.1	0.29	19.2
					2130.6	0.23	22.4
					2185.8	0.46	16.4
					2188.4	0.47	16.4
		15511.1	0.0			1.45	
4	599	19147.6	11389.1	53800.8	2250.0	14.54	2.0
					2323.1	0.36	20.5
					2347.7	0.18	26.7
					2372.4	0.70	11.9
					2404.9	0.47	13.2
					2428.5	0.81	13.2
		19147.6	0.0			2.52	
5	718	19929.0	12078.6	52477.6	2500.0	12.26	1.9
					2504.4	0.34	15.6
					2527.2	0.41	14.1
					2558.5	0.25	18.1
					2654.0	0.23	18.9
					2685.3	0.28	15.2
					2695.9	0.28	15.2
					2711.4	0.24	19.2
		19929.0	0.0			2.03	
6	837	21131.0	11885.9	51291.7	2750.0	11.05	1.8
					2904.0	0.21	17.5
					2936.1	0.38	12.8
					2989.1	0.16	18.6
		21131.0	0.0			0.75	
7	956	18473.4	11449.5	48166.6	3000.0	8.39	2.0
					3100.9	0.29	17.4
					3125.4	0.20	15.6
					3177.7	0.26	11.6
					3195.1	0.19	11.6
					3200.1	0.19	11.6
		18473.4	0.0			1.12	
8	1075	16017.6	10883.0	44086.8	3250.0	6.57	2.2
					3269.0	0.19	23.3
					3312.1	0.27	10.7
					3333.5	0.31	10.7
					3343.4	0.19	10.7

Table 5.6 Neodymium Pair Spectrometer Run 11211
GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 2

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
					3363.0	0.15	17.0
					3410.8	0.31	10.8
					3417.3	0.12	10.8
					3438.6	0.28	12.2
					3456.3	0.21	12.2
					3462.3	0.20	12.2
		16017.6	0.0			2.24	
9	1193	14395.4	9949.3	40343.0	3500.0	5.29	2.4
					3546.8	0.15	17.5
					3733.2	0.14	17.5
		14395.4	0.0			0.29	
10	1312	12083.8	9443.9	38146.1	3750.0	4.07	2.7
					3774.2	0.14	17.4
					3788.9	0.11	21.1
					3803.9	0.32	7.5
					3833.7	0.19	9.1
					3843.4	0.22	9.1
					3852.2	0.16	9.1
					3892.1	0.42	8.2
					3942.2	0.19	12.7
		12083.8	0.0			1.75	
11	1431	12872.0	8703.3	35532.1	4000.0	4.21	2.5
					4002.5	0.34	8.1
					4008.8	0.30	8.1
					4077.5	0.25	9.9
					4113.1	0.28	6.0
					4122.3	0.30	6.0
					4130.2	0.27	6.0
					4214.5	0.19	12.4
		12872.0	0.0			1.92	
12	1550	10311.6	7966.3	33082.6	4250.0	3.30	2.9
					4257.1	0.37	7.4
					4270.4	0.23	7.4
					4323.4	0.19	13.1
					4351.2	0.30	6.9
					4356.3	0.43	6.9
					4407.1	0.76	4.1
					4421.0	0.47	4.1
					4436.6	0.49	4.1
		10311.6	0.0			3.24	
13	1669	8367.7	7057.8	29698.3	4500.0	2.62	3.4
					4501.2	0.36	7.5
					4515.2	0.13	7.5
					4534.8	0.41	7.5
					4563.5	0.50	5.6
					4594.9	0.17	11.1

Table 5.6 (Continued) Nd PS GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 3

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
					4615.0	0.35	7.2
					4669.8	0.68	4.8
					4690.3	0.75	4.8
					4747.1	0.39	6.7
		8367.7	0.0			3.76	
14	1788	9497.2	6170.0	23716.6	4750.0	2.93	2.8
					4774.4	0.42	3.2
					4790.6	1.04	3.2
					4817.4	0.22	9.7
					4836.0	0.51	5.1
					4915.8	0.25	7.7
					4949.3	0.98	3.2
					4980.7	0.16	14.8
		9497.2	0.0			3.59	
15	1906	3440.1	6031.7	18240.8	5000.0	1.06	6.6
					5100.3	0.05	27.2
					5211.3	0.16	10.2
					5222.7	0.17	10.2
		3499.3	-59.3			0.38	
16	2025	4283.3	5108.0	19428.3	5250.0	1.33	5.4
					5380.8	0.90	3.4
					5448.4	1.66	2.3
		4292.1	-8.8			2.56	
17	2144	3479.2	4378.9	15328.9	5500.0	1.08	6.0
					5522.0	1.23	2.5
					5638.6	0.38	5.8
					5706.8	0.45	6.5
					5723.5	0.10	6.5
					5744.2	0.12	15.6
		3483.0	-3.8			2.29	
18	2263	2581.1	3980.1	13285.0	5750.0	0.80	7.5
					5787.5	0.15	11.0
		2616.7	-35.6			0.15	
19	2382	3926.1	3517.6	16436.7	6000.0	1.24	5.3
					6093.8	0.33	6.6
		3926.1	0.0			0.33	
20	2501	6369.3	2684.8	16546.3	6250.0	2.06	3.3
					6255.3	3.19	1.4
		6369.3	0.0			3.19	
21	2619	2352.1	2471.1	7326.1	6500.0	0.78	6.3
					6501.7	7.45	0.9
					6581.3	0.05	22.3
		2446.6	-94.5			7.49	
22	2738	360.6	2118.1	1648.0	6750.0	0.12	25.3
					6758.8	0.07	13.2
		570.3	-209.7			0.07	

Table 5.6 (Continued) Nd PS GAMAEC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 4

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	DEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
23	2857	775.5	1481.8	2228.6	7000.0	0.28	11.8
					7111.0	0.35	4.8
		854.7	-79.2			0.35	
24	2976	459.8	1577.8	1866.5	7250.0	0.18	19.0
		585.4	-125.6			0.0	
25	3095	979.2	1563.0	1864.9	7500.0	0.40	9.1
		1013.2	-34.0			0.0	
26	3214	-621.0	1306.2	-1151.5	7750.0	-0.27	5.3
		72.4	-693.4			0.0	
27	3332	-31.7	296.0	-77.2	8000.0	-0.01	79.9
		84.9	-116.6			0.0	
28	3451	94.5	191.0	44.0	8250.0	0.05	27.9
		159.0	-64.4			0.0	
29	3570	-95.7	281.3	-159.9	8500.0	-0.05	22.5
		62.2	-157.9			0.0	
30	3689	36.6	218.2	-106.5	8750.0	0.02	62.5
		168.6	-132.0			0.0	
31	3808	-17.6	224.5	-97.1	9000.0	-0.01	120.5
		87.6	-105.2			0.0	
32	3927	50.7	47.3	-38.5	9250.0	0.04	25.5
		99.8	-49.1			0.0	
33	4045	-9.2	25.4	-47.8	9500.0	-0.01	100.0
		16.1	-25.3			0.0	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 7480.00
UNRES = 47.5 -0.4 = 47.1%RES = 26.9%TOTAL = 73.8%
CS UNRES (EST) = 2.2% CS RES = 14.8% TOTAL ALL = 91.0%

NOTE: For shielding calculations, see table 10.1 which normalizes the above results so that 100% of the average sample binding energy is observed.

Table 5.6 (Continued) Nd PS GAMABC Results

5.4 Neodymium Comparison of Results

Table 5.7 gives a comparison of the results of this work with the published intensity data for the strong lines of neodymium. The energies of the gamma lines as found in this work are also given. The main source of published data used in this comparison is the Nuclear Data (ND-2) journal. Results from MITNE-85 (R-1) are also shown in table 5.7.

Table 5.7 shows that the results agree with the published intensities for Nd within the quoted accuracy of 10% to 20%. In general the results of this work gave intensities that were slightly higher than those of MITNE-85 and slightly lower than those given by Groshev for gamma lines below 4.5 MeV. At higher energies the listed results tend to be slightly higher than the published data, but the differences are usually within the estimated uncertainties of the listed values.

Table 5.7 Neodymium Comparison of Results

Strong Peaks Only, I > 0.30, I given in number of gammas of energy E per 100 captures in the sample.

Present Work		MIT-NB-85	Nuclear Data Tables (ND-2) Groshev 67Gr27	Groshev 67Gr27	Campion 59C04
Energy keV	semi I	semi I	s Cp I	semi I	cr, s Cp I
7111.0	0.35	0.31	0.35	0.31	0.35
6501.7	7.45	5.53	4.03	4.48	7.1
6255.3	3.19	2.51	2.3	1.91	3.2
6093.8	0.33	0.22	0.23	0.27	0.45
5706.8	0.45	0.30	0.38	0.35	0.6
5638.6	0.38	0.30	0.31	0.32	
5522.0	1.23	1.04	0.84	0.94	1.4
5448.4	1.66	1.20	1.15	1.0	1.4
5380.8	0.90	0.82	0.80	0.85	0.8
4949.3	0.98	0.85	0.97	0.68	1.9
4836.0	0.51	0.52	0.52	0.51	0.6
4790.6	1.04	0.78	0.70	0.60	1.6
4774.4	0.42	0.18	0.30	0.60	
4747.1	0.39	0.40	0.43	0.43	
4690.3	0.75	0.41	0.48	0.60	1.3
4669.8	0.68	0.49	0.51	0.60	
4615.0	0.35	0.30	0.35	0.43	
4563.5	0.51	0.44	0.49	0.43	
4534.8	0.41	0.30	0.50	0.43	0.7
4501.2	0.36	0.17	0.42	0.58	
4436.6	0.49	0.25	0.46	0.51	
4421.0	0.47	0.08	0.74	0.58	
4407.1	0.76	0.30			
4356.3	0.43	0.77	0.88	0.51	
4351.2	0.31				
4257.1	0.37	0.21	0.65	0.43	
4122.3	0.30	0.12	0.92	0.43	
4008.8	0.30	0.62	0.92		
4002.5	0.34				
3892.1	0.42	0.45	0.74		
3803.9	0.32	0.36			
3410.8	0.31	0.26			
3333.5	0.32	0.17			
2936.1	0.37	0.38			
2957.2	0.41	0.35			
2504.4	0.34	0.10			
2428.5	0.81	0.49			
2404.9	0.47	0.44			

Table 5.7 Continued Neodymium Comparison of Results

Present Work		MIT-NE-85 R1	Groshev 67Gr27	Groshev 67Gr27	Camplon 59C04	
Energy keV	semi I	semi I	s Cp I	semi I	cr, s Cp I	
2372.4	0.70	1.17				
2323.1	0.36	0.69				
2188.4	0.47	0.10				
2185.8	0.46	0.54				
1672.3	1.21	2.41			0.2	
1481.9	1.44	1.76	3.6			
1414.1	3.58	3.11	5.7		1.33	
1377.1	0.94	1.55	2.3		0.3	
1356.4	0.35				0.14	Draper 60Dr5 scin I
1341.3	0.55	0.77			0.13	
1138.0	1.06	1.31			0.4	
981.2	2.14	1.80	4.6		1.2	
864.9	11.15	8.82	12.5		7.5	7
814.7	9.28	8.87	12.0		6.6	7
779.3	1.71	1.53	4.0		1.4	
755.2	0.48					
742.7	6.83	5.90	8.2		5.4	
697.3	67.00	62.14	66.2		46	53
618.9	26.52	23.65	28.8		22.4	22
590.3	1.63	1.23			1.6	
564.5	1.30	1.15			1.1	
477.1	5.25	3.02			1.7 }	10
454.5	5.70	5.47			5.2 }	
426.6	1.77	1.38			0.8	
310.9	0.35	0.49				
201.0	0.65	0.36				

MITNE-104

Vol II
Chapters 6 - 10
Appendices

DETERMINATION OF THERMAL NEUTRON CAPTURE GAMMA YIELDS

by

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July, 1969

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6. SAMARIUM RESULTS

6.1 Samarium Sample

Table 6.1 list the sample characteristics and run information for samarium. Fifty milligrams of samarium oxide were mixed with about 1.0 grams of graphite powder (lampblack) in a poly vial of dimensions 7/8 inch diameter x 2 inches ling. The vial was approximately 1/2 full, which accounts for the fraction of the sample viewed by the Ge(Li) detector through the 1 inch diameter lead collimator as being less than 1.00.

The Westcott correction for samarium (Sm-149) is quite significant and indicates that there can be a large neutron spectrum affect on the results. This fact plus the large cross section of Sm-149 are indicated by the larger than usual uncertainty in the listed intensities for samarium. The effective capture cross section used for samarium was 1.25×10^4 barns, the average binding energy was 7981.9 keV, and flux depression factor was 0.787.

6.2 Samarium Compton Suppression Results

Figure 6.1 shows the samarium Compton suppression spectrum, run 12161, Tables 6.2 and 6.3 gives the GAMANL parameters and GAMANL results respectively. It is seen that 62 peaks were analysed and printed out for this data. The samarium peaks, background peaks, and marginal peaks are so labeled in column one, of Table 6.3.

TABLE 6.1 SAMARIUM SAMPLE DATA AND RUN INFORMATION

Sample: Sm_2O_2 At. Wt.: 150.4

Wt: 43.2 mg Sm Description: 50 mg Sm Oxide with 1.0 grams Lamp black in Poly Vial 7/8" diam x 2" Vial 1/2 full.

Holder: Al

Isotope: Sm^{149}

Natural%: 13.83

Thermal Capture : 41000b

Percent Captures in Natural Mixture: 100

Binding Energy of Product Nucleus: keV 7981.9

Effective Capture Cross Section: $\hat{\sigma}$ = 5828b

Westcott Correction: $\sigma_c = \hat{\sigma}(g + rs) = 5828(2.18-2.14(0.017)) = 1.25 \times 10^4$ b

Average Binding Energy for Sample: 7981.9 keV

Flux Depression Factor: $F_1 = 0.787$ $N_T\sigma_c = 2.16$ cm^2 $\rho x = 0.363$ gm/cm^2

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	12161	11151
Computer Job No:	J51204	J60276
Average Thermal Flux: ϕ(n/cm^{2}sec)	$1.83 \times 10^{+8}$	1.83×10^{8}
Fraction of Sample Viewed by 1" Collimator: F_2	0.69	0.585
Collimator Used: Diam.	1/2"	1/2"
Duration of Run (Min):	377	1506
Dead Time Corrected Run Time: (Min) t	320	1506
SANGLE	1.58×10^{-5}	1.58×10^{-5}
$FLUXT = F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	$4.13 \times 10^{+10}$	$1.64 \times 10^{+11}$

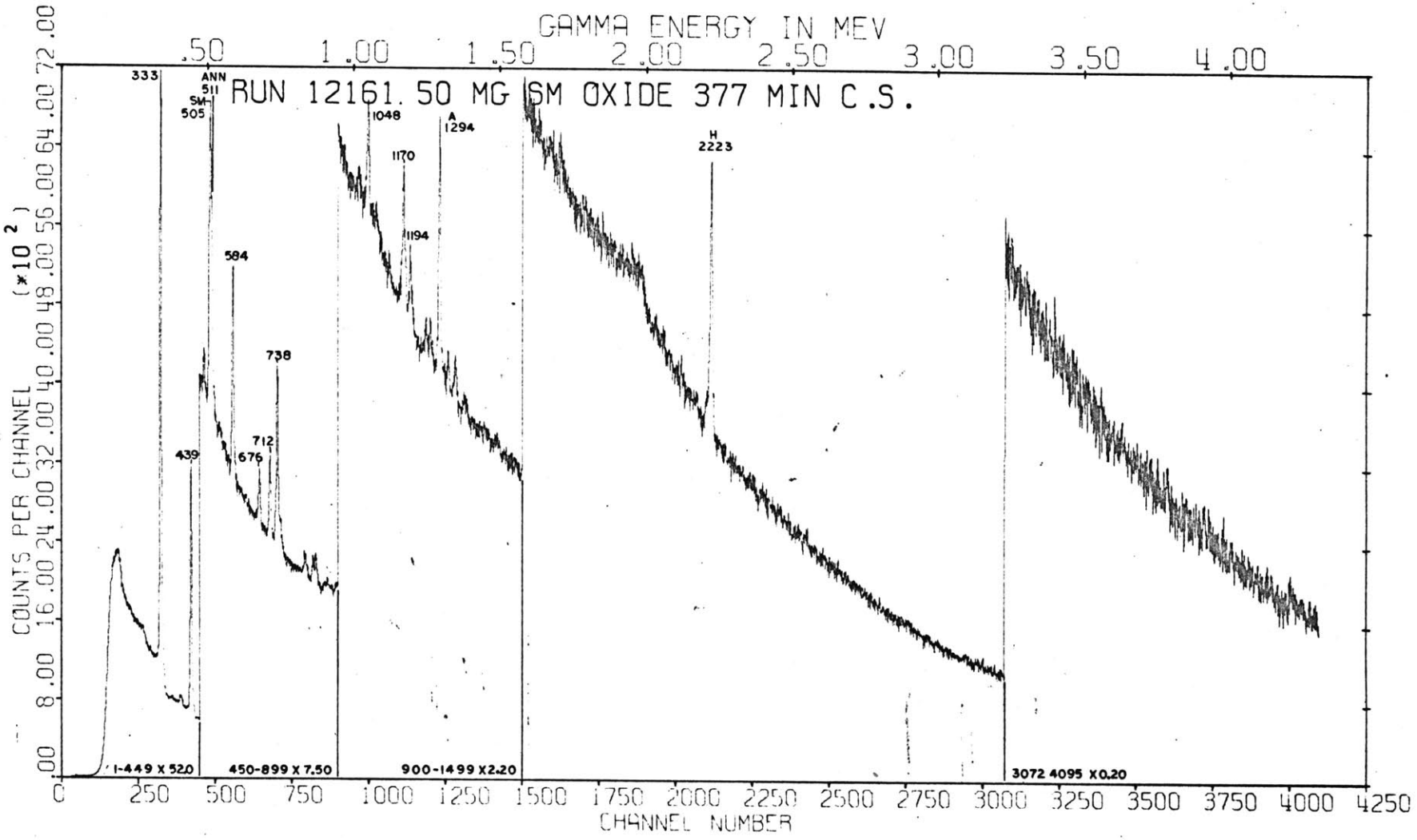

Figure 6.1 Samarium Compton Suppression Spectrum 12161

```
PARAMETERS AND INPUT DATA FOR RUN 12161  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  184
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  8.00 FWHM RANGE ERFW =  4.00
ENERGY PER CHANNEL NUMBER (KEV) = 1.053
CALIB1 E = 439.4 CNTR =  422 CORR = 419.6 FWHM =  5.82
CALIB2 E =2223.3 CNTR = 2114 CORR =2113.2 FWHM =  8.15
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.413E 11
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.525E-01 0.276E-01 0.183E-01 0.141E-01 0.114E-01
 0.103E-01 0.865E-02 0.739E-02 0.643E-02 0.573E-02
 0.502E-02 0.438E-02 0.389E-02 0.345E-02 0.306E-02
 0.257E-02 0.234E-02 0.212E-02 0.175E-02 0.160E-02
 0.140E-02 0.122E-02 0.104E-02 0.935E-03 0.853E-03
 0.760E-03 0.668E-03 0.606E-03.
NUMBER OF PEAKS ANALYSED = 63    J51204
```

Table 6.2 Samarium Compton Suppression Run 12161
GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1Sm	184.8	186.1	1359.8	0.0115	4183.7	28.2	0.116	3.10	0.55E-01	8.	S
					8291.3	18.1	0.230	5.64			
2Sm	209.6	208.7	1310.0	0.0140	3731.6	19.1	0.112	3.10	0.51E-01	5.	S
					8015.1	16.8	0.240	5.66			
3Sm	217.3	215.8	964.4	0.0106	3135.9	26.0	0.096	3.43	0.50E-01	6.	S
					5907.2	22.4	0.181	5.67			
4Sm	226.5	224.2	1748.6	0.0202	7351.8	13.5	0.232	5.68	0.48E-01	15.	D .002
					10731.4	12.1	0.339	5.68			
5Sm	235.0	232.0	1338.1	0.0154	5666.3	13.5	0.184	5.68	0.47E-01	15.	D .002
					8212.1	15.8	0.267	5.68			
6Sm	243.6	239.9	1388.7	0.0168	4286.1	18.2	0.143	3.25	0.46E-01	6.	S
					8538.0	14.9	0.285	5.69			
7Sm	252.1	247.8	2217.8	0.0273	11860.5	8.3	0.407	5.76	0.45E-01	10.	S *
					13651.6	9.3	0.469	5.70			
8Sm	261.3	256.3	1694.9	0.0213	5961.2	12.4	0.211	3.71	0.43E-01	7.	S *
					10447.0	12.0	0.369	5.70			
9Sm	271.6	265.7	3693.3	0.0490	20521.7	5.4	0.750	5.72	0.42E-01	16.	D .095
					22808.6	5.5	0.834	5.72			
10Sm	277.4	271.1	2073.0	0.0275	11575.8	5.4	0.431	5.72	0.41E-01	16.	D .095
					12801.7	9.6	0.477	5.72			
11Sm	285.8	278.9	1137.2	0.0162	5296.9	14.5	0.203	5.24	0.40E-01	8.	S *
					7034.0	16.7	0.269	5.73			
12Sm	296.6	289.0	3480.8	0.0521	14069.7	5.4	0.558	4.25	0.39E-01	8.	S *
					21564.5	5.5	0.855	5.73			
13Sm	305.4	297.1	846.2	0.0129	2821.4	21.0	0.115	3.56	0.37E-01	6.	S *
					5249.2	21.6	0.214	5.74			
14Sm	313.5	304.6	1051.5	0.0164	3152.9	18.6	0.132	3.24	0.36E-01	6.	S *
					6530.0	17.3	0.274	5.75			
15Sm	320.8	311.4	4007.6	0.0735	24872.6	0.2	1.067	5.76	0.36E-01	31.	D .000
					24940.4	4.4	1.070	5.76			

Table 6.3 Samarium Compton Suppression Run 12161 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
16Sm	333.4	323.1	315251.7	5.7846	1993612.0	0.2	89.155	5.76	0.34E-01	31.	D .000
					1961880.0	0.2	87.736	5.76			
17Sm	364.4	351.9	670.8	0.0158	2001.5	23.9	0.099	3.16	0.31E-01	6.	S *
					4197.5	22.1	0.208	5.79			
18Sm	372.5	359.4	1628.7	0.0387	7803.4	8.4	0.396	5.14	0.30E-01	9.	S *
					10204.1	9.2	0.518	5.80			
19Sm	381.7	368.0	917.8	0.0223	2940.9	16.0	0.154	3.39	0.29E-01	6.	S *
					5758.4	16.0	0.301	5.81			
20Sm	403.4	388.1	4583.9	0.1163	37313.0	3.2	2.080	8.69	0.27E-01	15.	S
					28853.0	3.4	1.609	5.83			
21Sm	425.8	409.0	749.7	0.0200	2321.7	21.7	0.136	3.25	0.26E-01	7.	S *
					4734.8	18.6	0.277	5.85			
22Sm	439.4	421.8	128730.4	3.6584	817659.4	0.2	49.246	5.82	0.25E-01	24.	S *
					814758.3	0.3	49.071	5.86			
23Sm	459.4	440.5	618.4	0.0195	2439.3	21.1	0.153	4.11	0.24E-01	8.	S *
					3926.2	20.7	0.247	5.88			
24Sm	485.5	465.1	2893.6	0.0974	13063.0	4.6	0.868	4.73	0.23E-01	10.	S *
					18446.0	4.6	1.225	5.90			
25Sm	505.9	484.3	23237.1	0.8368	229369.9	0.9	15.900	5.93	0.22E-01	33.	D .000
Ann					148839.6	0.8	10.317	5.93			
26Sm	525.4	502.6	563.0	0.0203	5573.8	0.9	0.402	5.93	0.21E-01	33.	D .000
					3606.4	21.3	0.260	5.93			
27Sm	536.4	513.0	758.9	0.0293	4692.1	11.7	0.346	5.95	0.21E-01	16.	D .114
					4879.0	15.4	0.360	5.95			
28Sm	541.7	517.9	647.5	0.0250	4002.4	11.7	0.298	5.95	0.20E-01	16.	D .114
					4162.7	18.0	0.310	5.95			
29Sm	570.1	544.7	825.4	0.0348	2981.0	13.5	0.235	3.84	0.19E-01	7.	S *
					5333.0	13.6	0.421	5.98			
30Sm	584.5	558.2	16018.5	0.6992	110268.3	1.0	8.941	6.15	0.19E-01	24.	S *
					103733.3	1.0	8.411	5.99			
31Sm	603.1	575.8	541.4	0.0247	1642.0	20.9	0.138	3.20	0.18E-01	6.	S *
					3516.9	19.8	0.295	6.01			

Table 6.3 (Continued) Sm CS

PEAK ANALYSIS PAGE 3

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE		
32Sm	629.1	600.3	663.5	0.0316	3293.0	14.0	0.286	5.36	0.18E-01	9.	S	*	
					4328.3	15.9	0.376	6.04					
33Sm	637.8	608.6	509.0	0.0247	1625.5	23.1	0.143	3.40	0.17E-01	7.	S	*	
					3325.0	20.4	0.292	6.05					
34Sm	676.1	644.7	3897.0	0.1999	26458.0	2.9	2.446	6.48	0.17E-01	17.	S	*	
					25618.6	3.0	2.368	6.08					
35Sm	712.4	679.1	5992.6	0.3249	41628.6	2.2	4.036	6.28	0.16E-01	22.	S	*	
					39634.9	2.1	3.843	6.12					
36Sm	737.6	703.0	13290.0	0.7675	97724.8	1.7	9.790	6.16	0.15E-01	41.	T	.000	.000
					88456.8	1.1	8.861	6.16					
37Sm	748.1	713.0	2486.9	0.1436	18290.2	1.7	1.857	6.16	0.15E-01	41.	T	.000	.000
					16552.6	4.2	1.681	6.16					
38Sm	762.9	727.1	427.7	0.0247	3145.7	1.7	0.325	6.16	0.15E-01	41.	T	.000	.000
					2847.1	22.3	0.295	6.16					
39Sm	772.2	735.9	565.5	0.0346	1903.4	19.5	0.199	3.58	0.15E-01	8.	S	*	
					3778.2	16.5	0.395	6.18					
40Sm	831.2	791.9	1668.8	0.1078	12844.6	6.3	1.446	6.25	0.14E-01	24.	D	.021	
					11271.9	5.8	1.269	6.25					
41Sm	838.8	799.1	702.7	0.0454	5413.8	6.3	0.615	6.25	0.13E-01	24.	D	.021	
					4746.4	13.1	0.539	6.25					
42Sm	859.0	818.3	1573.8	0.1047	11106.6	4.4	1.292	6.28	0.13E-01	24.	D	.002	
					10683.4	6.1	1.242	6.28					
43Sm	868.3	827.1	2102.0	0.1399	14885.0	4.4	1.749	6.28	0.13E-01	24.	D	.002	
					14268.8	4.7	1.677	6.28					
44Sm	898.8	856.0	447.0	0.0307	2096.7	18.3	0.255	5.00	0.13E-01	9.	S	*	
					3053.3	19.6	0.371	6.32					
45Sm	909.1	865.7	514.9	0.0350	2102.7	18.4	0.258	4.29	0.12E-01	9.	S	*	
					3523.1	17.2	0.433	6.33					
46Sm	941.3	896.1	741.7	0.0527	9952.6	11.0	1.264	13.59	0.12E-01	24.	S		
					5104.3	11.9	0.648	6.37					
47Sm	1016.1	967.3	477.3	0.0362	2353.8	16.9	0.317	5.35	0.11E-01	10.	S	*	
					3329.0	17.6	0.449	6.46					

Table 6.3 (Continued) Sm CS

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
48Sm1	1048.0	997.6	2100.7	0.1640	16674.4	3.7	2.277	8.07	0.11E-01	17.	S *
					14737.4	4.4	2.013	6.49			
49Sm1	1120.9	1066.2	549.4	0.0494	4055.0	14.1	0.574	7.13	0.11E-01	17.	S *
					3906.2	14.2	0.552	6.58			
50Sm1	1170.5	1113.1	2998.9	0.2811	28584.4	2.7	4.160	7.78	0.10E-01	24.	S *
					21520.3	3.1	3.132	6.64			
51Sm1	1194.2	1135.7	1461.6	0.1436	10897.2	6.2	1.610	6.68	0.10E-01	23.	D .178
					10541.9	5.6	1.557	6.68			
52Sm1	200.0	1141.2	476.4	0.0468	3602.3	6.2	0.534	6.68	0.10E-01	23.	D .178
B H DEP					3435.7	15.7	0.510	6.68			
53Sm1	247.2	1186.1	545.0	0.0561	2440.6	12.9	0.378	4.81	0.99E-02	9.	S *
					3968.3	13.5	0.614	6.74			
54Sm1	262.1	1200.3	629.2	0.0652	2306.7	12.5	0.362	3.90	0.97E-02	8.	S *
					4594.2	11.7	0.720	6.76			
B 55A	1293.7	1230.4	5331.8	0.5793	40719.1	1.8	6.563	7.09	0.95E-02	24.	S *
					39164.4	1.9	6.312	6.80			
56Sm1	323.6	1258.8	688.7	0.0787	4773.4	8.5	0.790	7.49	0.92E-02	13.	S *
					5087.7	10.3	0.842	6.84			
57Sm1	348.9	1282.7	872.6	0.1036	8766.3	6.6	1.482	9.84	0.90E-02	20.	S *
					6477.6	8.2	1.095	6.87			
58Sm1	447.3	1376.0	315.5	0.0412	1109.8	27.2	0.204	3.73	0.83E-02	8.	S
					2387.4	20.4	0.438	7.00			
59x	1700.9	1616.9	294.3	0.0481	932.0	22.8	0.207	3.36	0.69E-02	6.	S
					2342.5	19.7	0.521	7.37			
60Sm1	708.3	1623.9	323.5	0.0528	1547.1	17.6	0.346	5.11	0.68E-02	10.	S *
B H SEP					2579.0	18.0	0.576	7.38			
61Sm2	120.8	2016.1	234.1	0.0582	1019.0	18.2	0.294	4.65	0.53E-02	8.	S *
					2031.8	20.6	0.586	8.03			
B 62H	2223.3	2113.7	2695.7	0.7588	26659.0	2.3	8.248	8.15	0.49E-02	34.	S *
					23908.0	5.7	7.397	8.21			

Table 6.3 (Continued) Sm CS

6.3 Samarium Pair Spectrometer Results

Figure 6.2 shows the samarium pair spectrometer spectrum, run 11151. The spectrum shows a few well resolved samarium gamma peaks at energies greater than 5.0 MeV, and a large unresolved continuum portion of the spectrum at energies below 5.5 MeV.

Table 6.4 gives the GAMANL and GAMABC parameters for run 11151. Tables 6.5 and 6.6 present the GAMANL results and GAMABC results respectively. Table 6.5 shows that only 29 peaks were analysed and printed out for this samarium.data. Of these 20 are due to samarium.

Table 6.6 presents the results of the GAMABC analysis of the continuum. It is seen that there is a large intensity per bin width of 250 keV for samarium between 1.5 and 3.5 MeV. The total percent fraction of the average binding energy seen is 86.4%, which although low is within the expected accuracy of these calculations. This value is broken down as 15.2% being due to the well resolved lines of samarium, 66.6% being due to the unresolved continuum for energies greater than 1.5 MeV, and an estimated 4.6% being due to unresolved continuum for energies less than 1.5 MeV.

6.4 Samarium Comparison of Results

Table 6.7 shows a comparison of the results of this work with the published data for the intensities of the

strong capture lines of samarium. The energies of the gamma lines as found in this work are also given. The main source of the published intensities is Nuclear Data (ND-2). It is seen from the table that the results agree quite well with the published intensities. Good agreement is noted especially among the strong low energy (gamma energy below 1.5 MeV) lines of samarium.

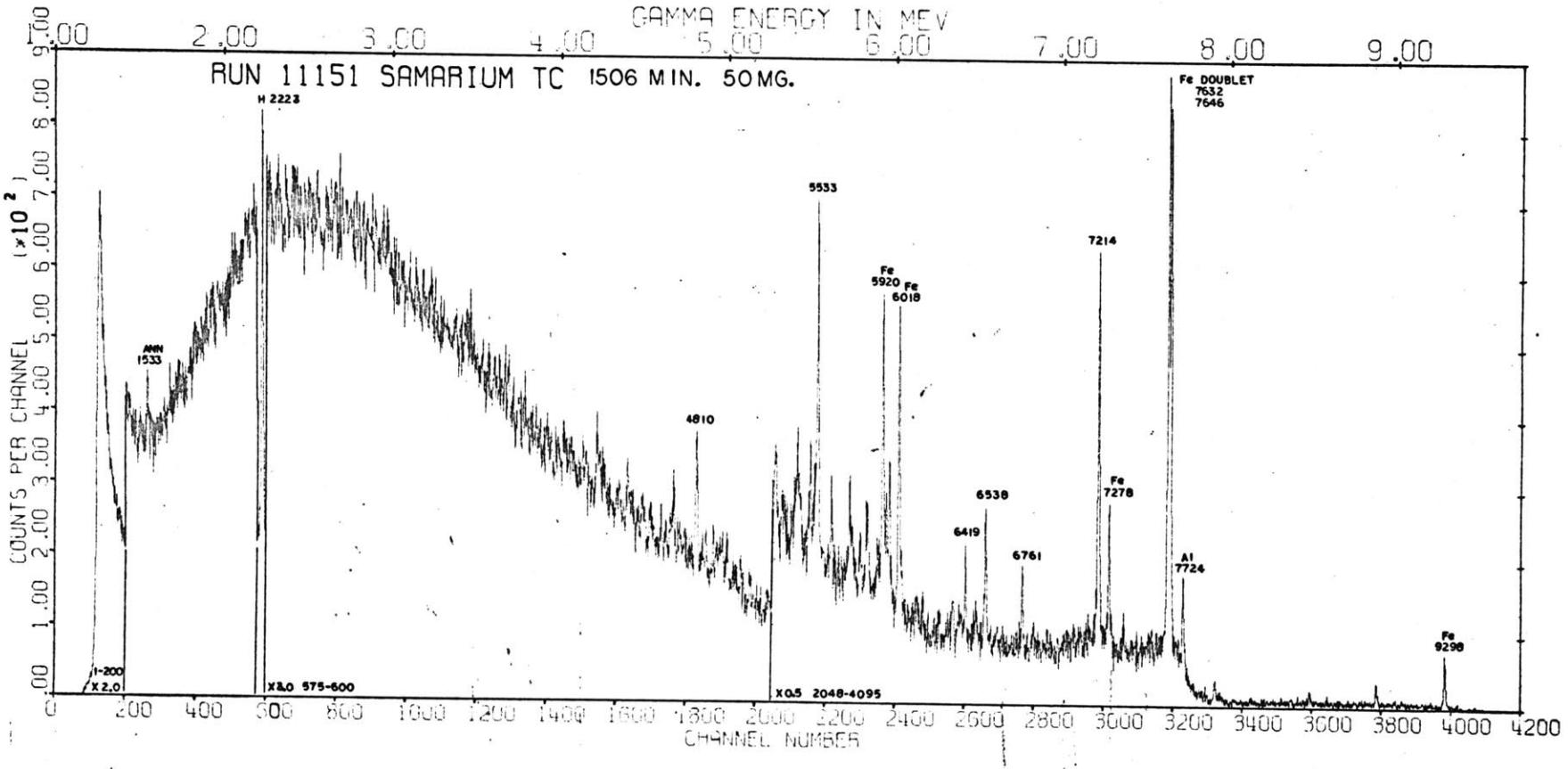

Figure 6.2 Samarium Pair Spectrometer Spectrum 11151

```
PARAMETERS AND INPUT DATA FOR RUN 11151  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  237
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  8.00 FWHM RANGE ERFW =  4.00
ENERGY PER CHANNEL NUMBER (KEV) = 2.084
CALIB1 E =2223.3 CNTR =  589 CORR = 588.7 FWHM =  8.83
CALIB2 E =7278.8 CNTR = 3016 CORR =3014.1 FWHM =  8.97
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.164E 12
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.927E-03
 0.915E-03 0.875E-03 0.813E-03 0.723E-03 0.637E-03
 0.550E-03 0.458E-03 0.369E-03 0.281E-03
NUMBER OF PEAKS ANALYSED = 29   J60276

GAMABC PEAK RESPONSE FUNCTION PARAMETERS
F2 = 0.00085 x AREA        F5 = 0.0014 x AREA
F3 = 0.00040 x AREA        F8 = 0.0042 x AREA
LOW CH = IMAX              MID CH = 900
W1 = 120 + 130 (E - 2200)/4610   for E ≤ 6810 keV
W1 = 250 + 125 (E - 6800)/ 850   for E > 6810 keV
W2 = 0.0004 x AREA + 2.0
W3 = 70
BAKFAC = 1.350  BIN WIDTH = 10 Chs  RED = 1.042
```

Table 6.4 Samarium Pair Spectrometer Run 11151
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
B	1	An1	531.8	262.4	95.8	0.2546	296.0	17.9	1.027	6.38	0.11E-03	7.	S *
							462.4	17.7	1.603	8.88			
B	2	H	2223.3	589.2	1766.8	2.5249	8805.2	2.0	10.215	8.83	0.33E-03	18.	S *
							8351.8	2.9	9.689	8.70			
	3	Sm3	691.5	1292.7	84.6	0.2140	475.8	19.3	0.229	12.66	0.80E-03	11.	S
							394.4	19.8	0.190	8.58			
	4	Sm4	216.8	1544.3	84.6	0.2876	771.6	17.4	0.336	13.42	0.88E-03	20.	S
							396.3	18.0	0.172	8.62			
	5	Sm4	676.8	1765.5	62.5	0.2450	213.5	24.4	0.089	5.92	0.92E-03	9.	S *
							295.0	22.0	0.124	8.69			
	6	Sm4	810.8	1829.8	186.0	0.9920	1424.7	7.2	0.592	14.08	0.93E-03	18.	S
							881.0	9.2	0.366	8.72			
	7	Sm4	869.8	1858.1	62.5	0.3295	213.9	19.6	0.089	6.58	0.93E-03	8.	S *
							296.7	20.0	0.123	8.73			
	8	Sm4	913.0	1878.9	75.6	0.4183	242.0	15.6	0.100	6.65	0.93E-03	7.	S *
							359.1	17.1	0.149	8.74			
	9	Sm5	078.0	1958.2	61.6	0.4107	259.8	14.7	0.107	9.73	0.93E-03	8.	S *
							294.0	18.9	0.121	8.78			
	10	Sm5	093.5	1965.7	58.3	0.4413	248.7	14.5	0.103	10.19	0.93E-03	8.	S *
							278.3	19.1	0.115	8.79			
	11	Sm5	281.9	2056.2	52.3	0.3995	371.4	15.6	0.154	16.38	0.93E-03	12.	S
							251.2	20.6	0.104	8.84			
	12	Sm5	491.8	2157.0	68.3	0.5526	254.0	15.0	0.105	6.93	0.93E-03	9.	S *
							330.7	16.7	0.137	8.91			
	13	Sm5	521.8	2171.3	46.4	0.3965	256.6	5.9	0.106	8.92	0.93E-03	21.	D .004
							224.8	21.9	0.093	8.92			
	14	Sm5	533.4	2176.8	242.4	2.0716	1347.9	5.9	0.559	8.92	0.93E-03	21.	D .004
							1174.6	7.4	0.487	8.92			
	15	Sm5	617.0	2217.2	49.9	0.4862	225.7	15.4	0.094	11.07	0.93E-03	9.	S *
							242.9	20.0	0.101	8.95			

Table 6.5 Samarium Pair Spectrometer Run 11151 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/10CC	KEV	N/CTS	CHAN	
16 Sm	5725.3	2269.3	46.0	0.4035	135.3	25.1	0.056	6.13	0.93E-03	7.	S
					224.5	21.9	0.093	8.99			
17 Fe	5921.8	2363.8	173.6	1.7100	973.8	5.6	0.408	10.92	0.92E-03	14.	S *
					854.9	8.8	0.358	9.07			
18 Sm	5963.5	2383.7	74.3	0.7317	284.5	11.6	0.119	8.14	0.92E-03	8.	S *
					366.5	15.0	0.154	9.08			
19 Fe	6019.4	2410.5	208.6	2.9383	1134.4	5.6	0.478	9.11	0.91E-03	21.	D .001
					1032.5	7.7	0.435	9.11			
20 Sm	6034.4	2417.8	37.2	0.5235	206.6	5.6	0.087	9.11	0.91E-03	21.	D .001
					184.0	22.6	0.078	9.11			
21 Sm	6419.4	2602.9	49.4	0.8707	178.0	13.9	0.078	6.80	0.88E-03	8.	S *
					249.3	17.6	0.109	9.29			
22 Sm	6538.3	2660.0	90.1	1.7678	496.6	7.4	0.219	10.12	0.87E-03	13.	S *
					457.4	11.9	0.202	9.35			
23 Sm	6760.6	2766.6	57.9	1.2528	258.5	11.2	0.118	8.09	0.85E-03	11.	S *
					297.7	15.4	0.135	9.46			
24 Sm	7214.2	2984.3	272.5	5.2748	1631.2	3.4	0.811	10.07	0.77E-03	18.	S *
					1439.9	6.6	0.716	9.72			
B 25 Fe	7278.8	3015.4	85.1	1.4784	364.0	8.2	0.184	8.97	0.76E-03	9.	S *
					451.6	12.6	0.228	9.76			
B 26 Fe	7633.0	3185.1	407.0	8.2196	2166.6	2.2	1.190	10.00	0.70E-03	25.	D .003
					2211.8	5.8	1.215	10.00			
B 27 Fe	7646.8	3191.7	376.6	7.6042	1987.9	2.2	1.096	10.00	0.70E-03	25.	D .003
					2046.2	6.0	1.128	10.00			
B 28 Al	7725.2	3229.2	53.7	1.3199	240.6	10.7	0.135	9.03	0.68E-03	10.	S *
					293.5	16.0	0.165	10.06			
B 29 Fe	9299.3	3981.6	25.4	2.6153	146.4	10.4	0.139	11.86	0.41E-03	13.	S *
					157.1	25.3	0.149	11.37			

Table 6.5 (Continued) Sm PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	243	3705.3	8982.6	34225.9	1500.0	10.17	8.1
		3743.5	-38.2			0.0	
2	363	11381.4	9551.7	39558.6	1750.0	19.94	2.9
		11381.4	0.0			0.0	
3	483	19706.9	10500.6	45320.3	2000.0	25.29	1.8
		19706.9	0.0			0.0	
4	602	25789.1	11511.2	44768.0	2250.0	26.27	1.4
		25789.1	0.0			0.0	
5	722	26684.3	12169.0	42033.2	2500.0	22.02	1.4
		26684.3	0.0			0.0	
6	842	25992.8	11978.1	38763.1	2750.0	18.23	1.4
		25992.8	0.0			0.0	
7	962	22373.6	11481.4	33888.0	3000.0	13.63	1.5
		22373.6	0.0			0.0	
8	1082	20245.9	11047.0	29474.7	3250.0	11.14	1.6
		20245.9	0.0			0.0	
9	1202	16828.4	9984.8	24895.2	3500.0	8.30	1.7
					3691.5	0.23	19.3
		16828.4	0.0			0.23	
10	1322	13835.0	9337.4	20787.6	3750.0	6.25	2.0
		13835.0	0.0			0.0	
11	1442	11899.1	8689.0	17676.2	4000.0	5.22	2.1
		11899.1	0.0			0.0	
12	1562	10269.9	7927.8	14700.1	4250.0	4.41	2.3
		10269.9	0.0			0.0	
13	1682	8319.6	6980.4	12412.8	4500.0	3.50	2.6
					4676.8	0.09	24.4
		8319.6	0.0			0.09	
14	1802	6870.7	6177.3	10195.3	4750.0	2.84	2.9
					4869.8	0.09	19.6
					4913.0	0.10	15.6
		6870.7	0.0			0.19	
15	1922	4040.9	5947.6	7575.1	5000.0	1.67	4.4
					5078.0	0.11	14.7
					5093.5	0.10	14.5
		4076.4	-35.5			0.21	
16	2042	3613.0	4994.1	6514.0	5250.0	1.50	4.5
					5281.9	0.15	15.6
					5491.8	0.11	15.0
		3685.4	-72.4			0.26	
17	2162	2300.8	4284.8	5438.4	5500.0	0.95	6.4
					5521.8	0.11	5.9
					5533.4	0.56	5.9
					5617.0	0.09	15.4
					5725.3	0.06	25.1

Table 6.6 Samarium Pair Spectrometer Run 11151
GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 2

BIN NO	L CH NC	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
		2335.4	-34.6			0.82	
18	2282	2617.3	3947.4	4679.0	5750.0	1.09	5.4
					5963.5	0.12	11.6
		2647.4	-30.1			0.12	
19	2402	718.0	3154.9	2754.3	6000.0	0.30	15.8
					6034.4	0.09	5.6
		911.4	-193.4			0.09	
20	2522	841.0	2750.7	2330.6	6250.0	0.37	12.7
					6419.4	0.08	13.9
		1004.2	-163.3			0.08	
21	2641	542.8	2239.0	2150.4	6500.0	0.24	18.0
					6538.3	0.22	7.4
		675.5	-132.7			0.22	
22	2761	374.6	1928.4	2165.2	6750.0	0.17	25.2
					6760.6	0.12	11.2
		560.7	-186.1			0.12	
23	2881	756.7	1527.3	3028.6	7000.0	0.37	13.2
					7214.2	0.81	3.4
		826.3	-69.7			0.81	
24	3001	699.9	1566.9	2659.0	7250.0	0.36	13.8
		758.2	-58.3			0.0	
25	3121	808.7	1774.4	2250.1	7500.0	0.44	11.7
		871.8	-63.0			0.0	
26	3241	49.8	676.4	-2.2	7750.0	0.03	83.4
		211.7	-161.9			0.0	
27	3361	29.1	196.2	17.4	8000.0	0.02	85.4
		110.3	-81.2			0.0	
28	3481	76.7	216.5	42.3	8250.0	0.05	35.4
		148.1	-71.4			0.0	
29	3601	-43.5	233.1	-74.8	8500.0	-0.03	52.8
		84.4	-128.0			0.0	
30	3721	29.9	247.3	-95.3	8750.0	0.02	82.9
		169.5	-139.6			0.0	
31	3841	7.0	155.7	-19.8	9000.0	0.01	300.2
		91.3	-84.2			0.0	
32	3961	90.8	27.2	5.6	9250.0	0.10	16.5
		124.9	-34.1			0.0	
33	4081	1.6	2.7	-1.8	9500.0	0.00	154.3
		2.8	-1.3			0.0	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 7981.90
UNRES = 66.6 -0.0 = 66.6%RES = 2.4%TOTAL = 69.0%
CS UNRES (EST) = 4.6% CS RES = 12.8% TOTAL ALL = 86.4%
NOTE: For shielding calculations, see table 10.1 which normalizes the above results so that 100% of the average binding energy of the sample is observed.

Table 6.6 (Continued) Sm PS GAMABC Results

Table 6.7 Samarium Comparison of Results

Strong Peaks only, $I \geq 0.10$ ($E > 1500$ keV), $I \geq 0.20$ ($E < 1500$ keV), I given in number of gamma rays of energy E per 100 captures in the sample.

Present Work		MIT-NE-85	Nuclear Data Tables (ND-2)		
		R-1	Groshev	Smither	
			63Gr18	66Sm03	
Energy keV	semi I	semi I	s Cp I	cryst I	
7214.2	0.81	0.75	0.47		
6760.6	0.12				
6583.3	0.22	0.20	0.12		
5963.5	0.12	0.14	0.16		
5533.4	0.56	0.48	0.40		
5521.8	0.11				
5491.8	0.10	0.12	0.14		
5281.9	0.15	0.11	0.13		
5093.4	0.10	0.05			
5078.0	0.11	0.05	0.09		
4913.0	0.10		0.12		
4810.8	0.59	0.39	0.19		
4216.8	0.34	0.03	0.07		
3691.5	0.23	0.08			
2120.8	0.29	0.40	0.60	0.42	
1708.3	0.35	0.22	0.4	0.36	
1447.3	0.20	0.32	0.1	0.23	
1348.9	1.48	2.22	1.9	1.17	
1323.6	0.79	1.22	1.5	0.95	
1262.1	0.36	1.15	0.6	0.81	
1247.2	0.38	0.55	0.9	0.56	
1194.2	1.61	2.61	3.0	1.21,0.24*	
1170.5	4.16	4.42	5.8	2.07,0.89*	
1120.9	0.57	0.35	0.8	0.4	
1048.0	2.28	2.63	2.7	1.77	
1016.1	0.32			0.50	
941.3	1.26	0.25	0.8	0.44	
909.1	0.26		1.5	0.51	
898.8	0.26	0.24	0.6	0.29	
868.3	1.75	1.07	1.8	1.30	
859.0	1.29	0.53	1.7	1.03	
838.8	0.61			0.27	Bieber
831.2	1.45	1.45	1.7	0.77	cryst
762.9	0.32	0.27		0.18	62Bi16
748.1	1.86	1.60	1.9	1.08	I
737.6	9.79	9.27	14	6.56	5.5
712.4	4.04	3.93	6.2	3.07	2.0

* Multiple line

Table 6.7 (Continued) Samarium Comparison of Results

Present Work		MIT-NE-85 R-1	Groshev 63Gr18	Smither 66Sm03	Bieber 62Bi16
Energy keV	semi I	semi I	s Cp I	cryst I	cryst I
676.1	2.45	2.07	2.9	1.99	1.9
629.1	0.29	0.30		0.09	
584.5	8.94	7.67	9.3	6.05	5.2
570.1	0.24	0.32		0.27	
541.7	0.30	0.46		0.17	
536.4	0.35			0.10	
525.4	0.40	0.19		0.02	
505.9	15.90*	13.80*	10	6.58	6.9
485.5	0.87	1.06	2.2	0.81	
439.4	49.25	45.79	54	35.7	34.8
403.4	2.08	1.46		0.89	1.00
372.5	0.40			0.26	
333.4	89.16	83.26	82	60.9	67.6
320.8	1.07			0.01	
296.6	0.56	0.40		0.50	0.51
285.8	0.20			0.12	
277.4	0.43	0.73		0.02	
271.6	0.75	0.60		0.01	
261.3	0.21	0.08		0.02	
252.1	0.41	0.10		0.23	0.22
226.5	0.23				0.01

* 511.0 Annihilation peak interference.

7. EUROPIUM RESULTS

7.1 Europium Sample

Table 7.1 lists the sample characteristics and run information for europium. The sample consisted of 114.25 milligrams of europium oxide mixed with 1.9 grams of graphite powder (lampblack) in a poly vial of dimensions 3/4 inch diameter x 1 3/4 inches long. The majority of the captures occur in Eu-151 which contributes 96% of the thermal captures in the natural sample. The effective capture cross section for the sample was 4400 barns, which was corrected using the Westcott factors to 3700 barns. The average binding energy of the sample was 6294.8 keV and the flux depression factor was 0.909.

7.2 Europium Compton Suppression Results

Figure 7.1 shows the europium Compton suppression spectrum, run 11213, Tables 7.2 and 7.3 give the GAMANL results and GAMANL parameters for this data. A total of 26 peaks were analysed with 16 peaks being due to the europium sample. Two gamma peaks from electron capture decay of Eu-152 at gamma energies 841.3 keV and 964.3 keV are labeled as decay lines in Table 7.3. The 14 europium capture peaks, 3 background peaks, and 7 marginal peaks (tentatively assigned to europium) are also labeled in column one of Table 7.3.

TABLE 7.1 EUROPIUM SAMPLE DATA AND RUN INFORMATION

Sample: Eu_2O_3 At. Wt.: 152.0

Wt: 100 mg Eu Description: 114.25 Eu Oxide in 1.9 grams Lampblack in Poly Vial 3/4" diam x 1 3/4" Full Vial

Holder: Al

	Eu^{151}	Eu^{153}
Isotope:		
Natural %:	47.82	52.18
Thermal Capture :	8800b	390b
Percent Captures in Natural Mixture:	96	4
Binding Energy of Product Nucleus: keV	6291	6385

Effective Capture Cross Section: σ = 4400b

Westcott Correction: $\sigma_c = \sigma(g + rs) = 4400(0.814 + 1.32\ (0.017))$

σ_c = 3700b

Average Binding Energy for Sample: 6294.8 keV

Flux Depression Factor: F_1 = 0.909 $N_T\sigma_c$ = 1.46 cm^2 $\rho\bar{x}$ = 0.78 gm/cm^2

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	11213	11221
Computer Job No:	J40596	J20052
Average Thermal Flux: ϕ ($n/cm^2 sec$)	$1.83 \times 10^{+8}$	$1.83 \times 10^{+8}$
Fraction of Sample Viewed by 1" Collimator: F_2	1.00	1.00
Collimator Used:	1/2"	1/2"
Duration of Run (Min):	170	1210
Dead Time Corrected Run Time: (Min) t	143	1210
SANGLE	1.58×10^{-5}	1.58×10^{-5}
FLUXT = $F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	$2.08 \times 10^{+10}$	$1.74 \times 10^{+11}$

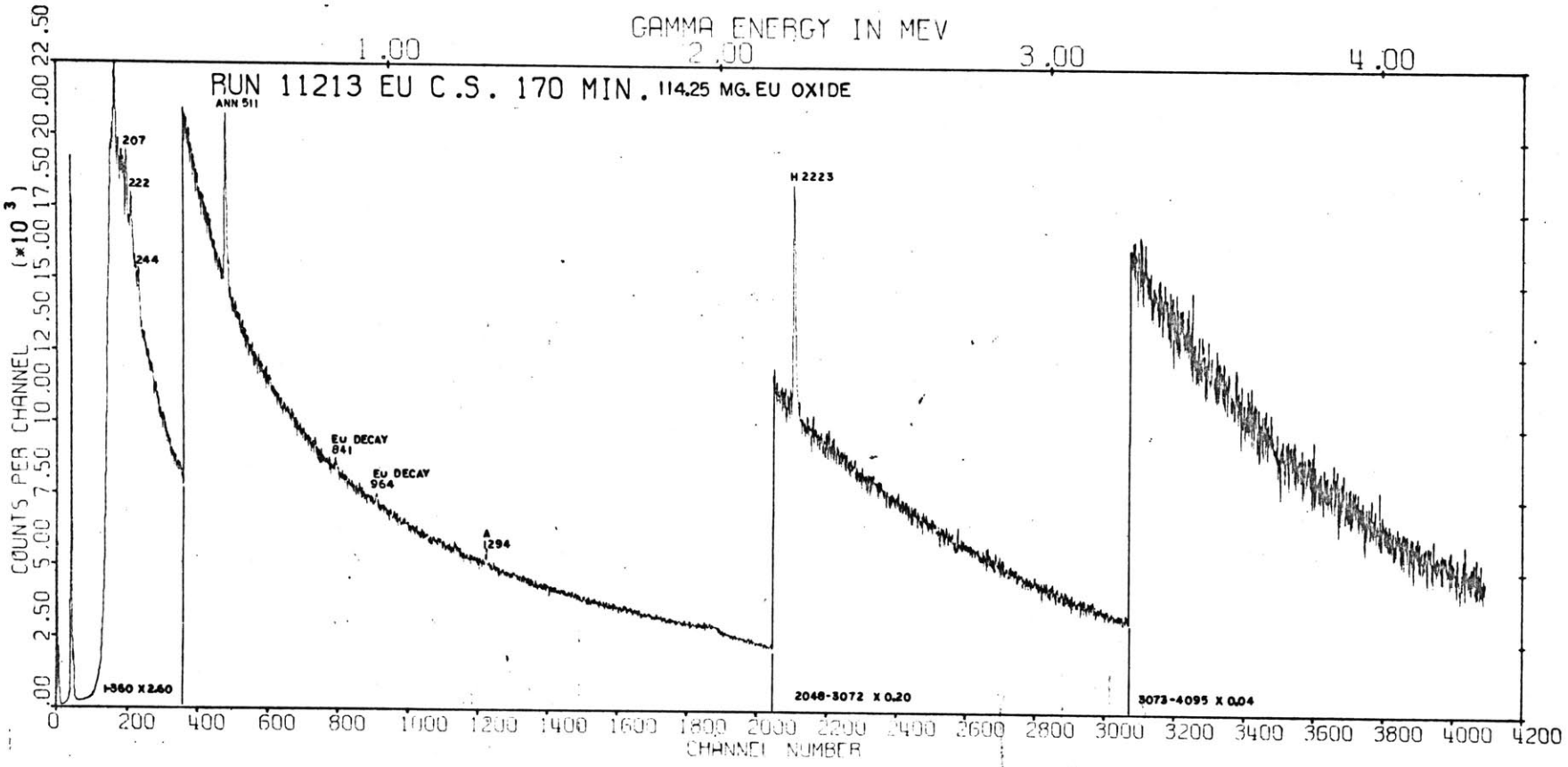

Figure 7.1 Europium Compton Suppression Spectrum 11213

```
PARAMETERS AND INPUT DATA FOR RUN 11213  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  174
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  7.00 FWHM RANGE ERFW =  3.00
ENERGY PER CHANNEL NUMBER (KEV) = 1.053
CALIB1 E = 511.0 CNTR =  482 CORR = 480.6 FWHM =  6.51
CALIB2 E =2223.3 CNTR = 2107 CORR =2106.9 FWHM =  6.93
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.208E 11
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.369E-01 0.255E-01 0.175E-01 0.136E-01 0.111E-01
 0.101E-01 0.835E-02 0.715E-02 0.622E-02 0.555E-02
 0.486E-02 0.425E-02 0.379E-02 0.336E-02 0.298E-02
 0.251E-02 0.229E-02 0.207E-02 0.172E-02 0.157E-02
 0.138E-02 0.120E-02 0.103E-02 0.908E-03 0.828E-03
 0.738E-03 0.650E-03 0.590E-03
NUMBER OF PEAKS ANALYSED = 26     J40596
```

Table 7.2 Europium Compton Suppression Run 11213
GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE
					AREA-G	ERR-G	INT-G	FWHM-C			
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1Eu	181.3	176.0	1159.2	0.0232	3050.3	17.1	0.243	2.86	0.38E-01	5.	S
					5938.4	14.2	0.472	5.14			
2Eu	191.9	185.7	1443.8	0.0296	5750.4	14.6	0.466	3.97	0.37E-01	9.	S
					7425.9	11.4	0.602	5.16			
3Eu	198.5	191.7	1869.4	0.0396	5438.2	10.8	0.446	3.11	0.37E-01	6.	S
					9638.6	8.8	0.790	5.17			
4Eu	206.6	199.1	5243.3	0.1157	25175.0	3.0	2.094	5.05	0.36E-01	10.	S *
					27114.7	3.9	2.255	5.19			
5Eu	221.6	212.9	3950.5	0.0927	21485.5	3.9	1.836	5.56	0.36E-01	12.	S *
					20540.8	4.5	1.755	5.22			
6Eu	233.5	223.8	824.8	0.0208	2453.2	18.8	0.214	3.15	0.35E-01	6.	S *
					4307.1	17.5	0.376	5.24			
7Eu	244.1	233.6	2157.7	0.0581	11098.7	6.1	0.987	5.47	0.34E-01	10.	S *
					11309.7	6.9	1.006	5.26			
8x	262.1	250.1	582.2	0.0175	2343.3	22.5	0.215	4.28	0.33E-01	8.	S *
					3070.6	22.6	0.282	5.29			
9Eu	286.2	272.4	847.0	0.0282	3123.4	14.5	0.300	3.95	0.32E-01	7.	S *
					4504.7	14.9	0.433	5.34			
10Eu	296.1	281.5	1120.8	0.0405	5910.5	9.9	0.578	5.36	0.31E-01	15.	D .069
					5987.2	11.0	0.586	5.36			
11Eu	302.1	287.2	780.5	0.0282	4171.1	9.9	0.413	5.36	0.31E-01	15.	D .069
					4169.3	15.5	0.413	5.36			
12Eu	320.3	304.0	759.6	0.0296	4139.1	18.8	0.424	4.02	0.30E-01	15.	S *
					4086.4	15.4	0.418	5.40			
13x	355.2	336.5	617.4	0.0276	2070.1	18.9	0.226	3.57	0.28E-01	7.	S *
					3359.2	17.6	0.367	5.46			
14Eu	389.5	368.3	464.8	0.0233	1581.9	23.4	0.184	3.61	0.26E-01	7.	S *
					2556.3	22.0	0.298	5.52			
15Eu	424.0	400.5	521.2	0.0287	1912.5	18.4	0.239	3.91	0.24E-01	7.	S *
					2896.6	18.8	0.361	5.58			

Table 7.3 Europium Compton Suppression Run 11213 GAMANL Results

PEAK ANALYSIS PAGE 2

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
	16x	440.5	415.9	423.1	0.0242	1527.6	25.1	0.197	3.82	0.24E-01	8.	S *
						2362.8	22.6	0.304	5.60			
	17Eu	458.4	432.6	420.2	0.0251	1360.4	24.9	0.181	3.48	0.23E-01	7.	S *
						2358.6	22.4	0.315	5.63			
B	18An	511.0	482.2	5737.4	0.3859	39666.4	1.9	5.854	6.51	0.21E-01	19.	S *
						32688.1	2.5	4.824	5.72			
	19x	610.1	575.5	358.3	0.0303	1087.5	26.1	0.191	3.26	0.17E-01	7.	S *
						2094.9	22.2	0.368	5.87			
	20x	644.4	607.9	346.6	0.0308	1348.5	22.8	0.248	4.09	0.17E-01	8.	S *
						2043.6	22.4	0.375	5.92			
	21x	779.8	736.2	317.5	0.0351	1051.9	23.7	0.229	3.49	0.14E-01	7.	S *
						1930.0	22.3	0.420	6.10			
D	22Eu	841.3	794.6	301.9	0.0357	1133.9	23.6	0.265	3.92	0.13E-01	8.	S *
						1858.6	22.7	0.435	6.18			
D	23Eu	964.3	911.2	397.0	0.0555	1904.8	17.9	0.505	4.58	0.11E-01	12.	S *
						2499.6	16.8	0.663	6.32			
B	24A	1294.2	1224.1	371.4	0.0737	1861.9	13.3	0.613	5.33	0.92E-02	10.	S *
						2448.7	16.0	0.807	6.62			
	25x	1564.4	1480.6	207.2	0.0533	824.7	22.1	0.341	4.21	0.73E-02	8.	S *
						1399.0	23.1	0.578	6.77			
B	26H	2223.3	2107.3	1530.7	0.7282	11737.7	3.3	7.447	6.92	0.48E-02	27.	S *
						10414.9	5.9	6.607	6.83			

D - Decay Gamma Ray

Table 7.3 (Continued) Eu CS

7.3 Europium Pair Spectrometer Results

Figure 7.2 shows the europium pair spectrometer spectrum, run 11221. Very few strong well resolved peaks are seen in Figure 7.2, while a large unresolved continuum is present over the energy range 1.5 MeV to 5.0 MeV.

Table 7.4 gives the GAMANL and GAMABC parameters for run 11221. Tables 7.5 and 7.6 present the GAMANL results and GAMABC results respectively. A total of 31 resolved peaks were analysed with 10 peaks rejected by the error criterion, and 21 peaks printed out. Of these, 7 peaks are assigned to europium, 4 peaks are marginal and tentatively assigned to europium, and 10 peaks are background lines.

The GAMABC results of analysis of the unresolved continuum are presented in Table 7.6. There is a large intensity per bin width of 250 keV for europium in the gamma energy range 1.5 MeV to 3.5 MeV. The total percent fraction observed of the average binding energy of europium is 86.3%. This is broken into 1.7% being due to the resolved lines of europium (with the decay lines not included in this percent calculation), and 84.6% being due to the unresolved continuum. Of this, 78.5% is due to the continuum above 1.5 MeV, and 6.1% is estimated as from the continuum below 1.5 MeV.

7.4 Europium Comparison of Results

Table 7.7 shows a comparison of the results of this

work with the published data for the intensities of the strong capture lines of europium. The energies of the gamma lines as found in this work are also given. The main source of published listing of these intensities is Nuclear Data (ND-2). Europium basically does not have any very strong capture gamma lines. This is evident from Figures 7.1 and 7.2 and from Table 7.7, in that the strongest high energy line is at 6069.7 keV with 0.13 gamma rays emitted per 100 captures in the sample. At low energies the strongest observed lineis at 206.6 keV with 2.09 gammas emitted per 100 captures in the sample. The lack of strong lines makes comparison of these results with other data quite arbitrary. In general the low intensities of the observed lines imply a high uncertainty in the listed values. With this in mind, the columns of Table 7.7 agree within the expected accuracy.

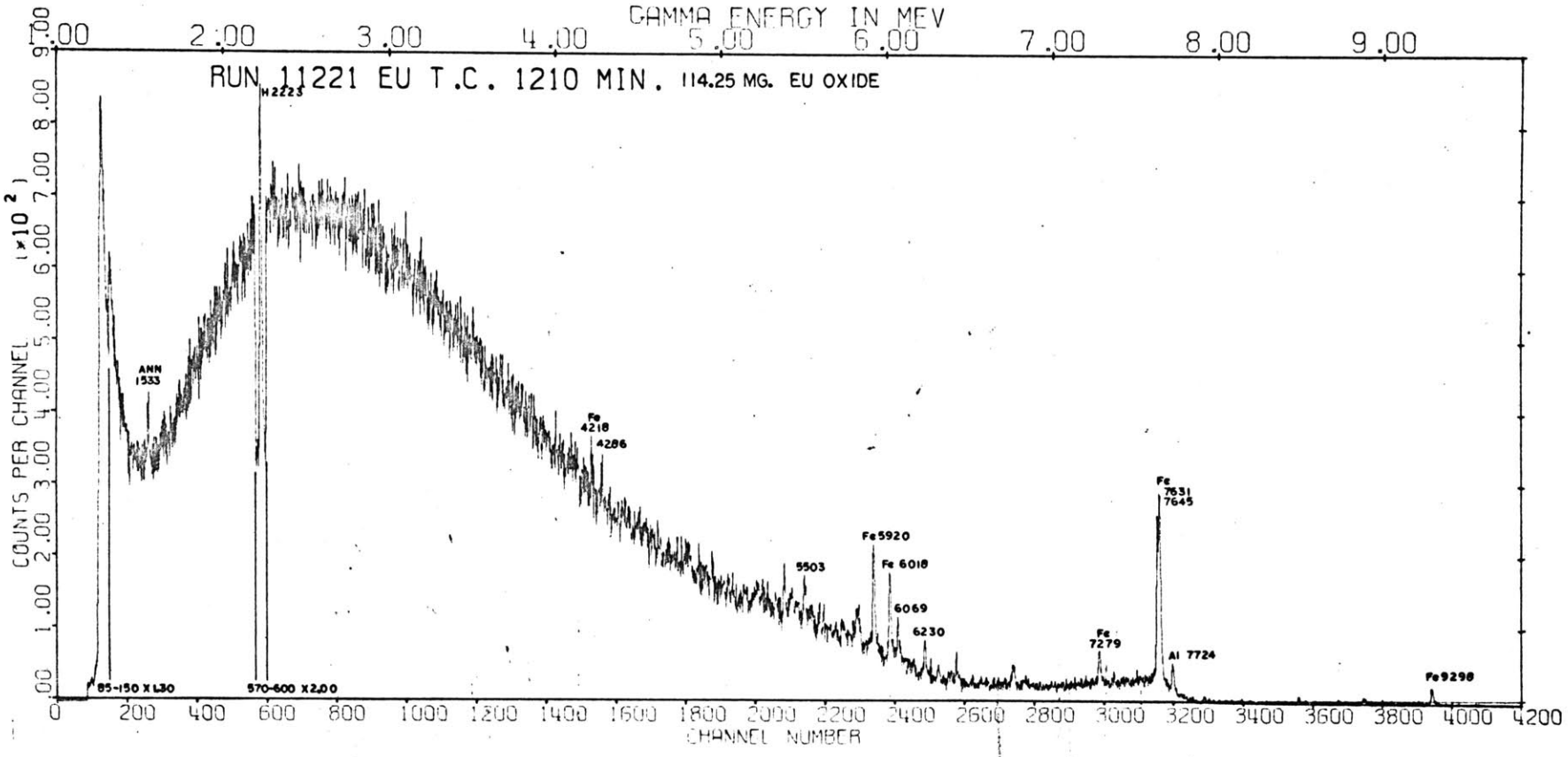

Figure 7.2 Europium Pair Spectrometer Spectrum 11221

```
PARAMETERS AND INPUT DATA FOR RUN 11221  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  200
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   3.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   2.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS = 11.00 FWHM RANGE ERFW =  5.00
ENERGY PER CHANNEL NUMBER (KEV) = 2.106
CALIB1 E =2223.3 CNTR =  584 CORR = 583.7 FWHM = 14.32
CALIB2 E =7723.8 CNTR = 3197 CORR =3195.7 FWHM = 15.85
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.174E 12
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.927E-03
 0.915E-03 0.875E-03 0.813E-03 0.723E-03 0.637E-03
 0.550E-03 0.458E-03 0.369E-03 0.281E-03
NUMBER OF PEAKS ANALYSED = 31   J20052

GAMABC PEAK RESPONSE FUNCTION PARAMETERS
F2 = 0.00085 x AREA      F5 = 0.00150 x AREA
F3 = 0.00045 x AREA      F8 = 0.00450 x AREA
LOW CH = IMAX            MID CH = 900
W1 = 120 + 130 (E - 2200)/4610  for E ≤ 6810 keV
W1 = 250 + 125 (E - 6800)/ 450  for E > 6810 keV
W2 = 0.0004 x AREA + 2.0
W3 = 70
BAKFAC = 1.100  BIN WIDTH = 10 CHS   RED = 1.045
```

Table 7.4 Europium Pair Spectrometer Run 11221
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE
						AREA-G	ERR-G	INT-G	FWHM-C			
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
B	1An	1536.7	263.1	66.2	0.1903	304.2	20.1	0.980	9.91	0.11E-03	9.	S *
						517.1	26.0	1.667	16.34			
B	2H	2223.3	584.2	1028.8	1.4640	6977.1	2.5	7.629	14.32	0.33E-03	18.	S *
						6610.8	7.0	7.228	13.44			
	3x	3067.7	984.6	62.0	0.1053	261.1	27.4	0.154	8.97	0.61E-03	8.	S *
						317.1	31.0	0.188	10.69			
	4x	3857.9	1359.4	56.6	0.1490	234.6	24.7	0.102	9.02	0.84E-03	8.	S *
						241.8	29.8	0.105	8.94			
	5x	3873.3	1366.7	66.3	0.1797	173.2	23.4	0.075	5.54	0.84E-03	5.	S *
						282.7	26.4	0.122	8.91			
B	6Fe	4217.7	1530.1	45.7	0.1421	96.8	32.9	0.040	4.64	0.88E-03	4.	S *
						183.5	34.4	0.075	8.40			
	7Eu	4286.0	1562.3	52.1	0.1788	128.5	27.9	0.052	5.06	0.89E-03	5.	S *
						207.0	30.6	0.084	8.32			
	8Eu	5503.4	2141.5	54.5	0.4355	231.5	16.1	0.091	7.82	0.93E-03	13.	D .164
						203.8	27.9	0.080	7.82			
	9Eu	5597.7	2186.2	33.9	0.2960	98.8	29.3	0.039	6.17	0.93E-03	7.	S *
						127.3	34.1	0.050	7.86			
B	10Fe	5920.9	2340.2	127.4	1.3397	828.4	6.9	0.327	13.77	0.92E-03	13.	S
						492.3	21.6	0.194	8.08			
B	11Fe	6019.8	2387.2	106.1	1.3073	713.6	8.2	0.283	13.77	0.91E-03	15.	S
						414.9	21.9	0.165	8.18			
	12Eu	6069.7	2410.9	51.6	0.7127	320.2	13.6	0.127	10.42	0.91E-03	15.	S *
						203.2	25.8	0.081	8.23			
	13Eu	6229.8	2487.2	40.6	0.7891	219.3	14.2	0.088	11.16	0.90E-03	12.	S *
						163.5	26.7	0.066	8.42			
	14Eu	6311.3	2526.0	21.5	0.5908	162.5	19.3	0.066	13.94	0.89E-03	16.	S *
						87.8	33.4	0.036	8.53			
	15Eu	6418.7	2577.2	24.5	0.6043	95.8	19.1	0.039	8.28	0.88E-03	7.	S *
						101.8	31.7	0.042	8.68			

Table 7.5 Europium Pair Spectrometer Run 11221 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S / AREA-G	ERR-S / ERR-G	INT-S / INT-G	FWHM-M / FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
16x	6760.6	2739.4	25.5	0.7112	212.6	17.0	0.091	18.09	0.85E-03	15.	S
					113.3	29.8	0.049	9.28			
B 17Fe	7281.9	2987.1	47.0	1.3435	334.5	9.2	0.159	14.30	0.76E-03	14.	S *
					235.3	22.9	0.112	10.47			
B 18Fe	7633.5	3153.9	219.5	4.9880	1407.4	2.7	0.729	11.48	0.70E-03	26.	D .035
					1205.2	17.9	0.624	11.48			
B 19Fe	7646.4	3160.0	248.5	5.6466	1596.1	2.7	0.829	11.48	0.70E-03	26.	D .035
					1364.3	17.7	0.709	11.48			
B 20Fe	7723.8	3196.8	36.7	1.5001	292.3	10.3	0.155	15.85	0.68E-03	18.	S *
					206.2	25.1	0.109	11.75			
B 21Fe	9299.3	3942.1	20.7	2.4844	132.6	10.3	0.119	15.14	0.41E-03	12.	S *
					181.3	45.6	0.162	18.31			

Table 7.5 (Continued) Eu PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	241	1673.8	7225.4	33821.6	1500.0	4.33	17.3
					1536.7	0.98	20.1
		1940.4	-266.6			0.98	
2	360	10014.0	7710.4	40227.4	1750.0	16.53	3.2
		10014.0	0.0			0.0	
3	479	18751.4	8481.0	46433.0	2000.0	22.68	1.9
		18751.4	0.0			0.0	
4	597	25154.1	9247.3	46793.4	2250.0	24.15	1.5
		25154.1	0.0			0.0	
5	716	26431.6	9836.6	44562.7	2500.0	20.56	1.4
		26431.6	0.0			0.0	
6	835	25185.7	9633.8	41308.6	2750.0	16.65	1.4
		25185.7	0.0			0.0	
7	954	23803.0	9210.3	36910.8	3000.0	13.67	1.4
					3067.7	0.15	27.4
		23803.0	0.0			0.15	
8	1072	21597.8	8920.2	32207.4	3250.0	11.20	1.5
		21597.8	0.0			0.0	
9	1191	18882.9	8081.4	27218.8	3500.0	8.78	1.6
		18882.9	0.0			0.0	
10	1310	15317.9	7596.6	22358.8	3750.0	6.53	1.8
					3857.9	0.10	24.7
					3873.3	0.07	23.4
		15317.9	0.0			0.18	
11	1428	13065.8	7055.1	18395.5	4000.0	5.41	1.9
		13065.8	0.0			0.0	
12	1547	9982.2	6480.4	14795.9	4250.0	4.04	2.3
					4286.0	0.05	27.9
		9982.2	0.0			0.05	
13	1666	8175.2	5672.6	12037.3	4500.0	3.24	2.6
		8175.2	0.0			0.0	
14	1785	6809.9	5029.0	9678.1	4750.0	2.65	2.8
		6809.9	0.0			0.0	
15	1903	5090.6	4904.9	7992.3	5000.0	1.98	3.5
		5090.6	0.0			0.0	
16	2022	5210.8	4125.8	6905.4	5250.0	2.04	3.2
		5210.8	0.0			0.0	
17	2141	3891.4	3511.4	5401.8	5500.0	1.52	3.8
					5503.4	0.09	16.1
					5597.7	0.04	29.3
		3891.4	0.0			0.13	
18	2259	3113.2	3181.1	4254.9	5750.0	1.23	4.3
		3124.2	-11.0			0.0	
19	2378	1566.3	2836.4	2299.8	6000.0	0.63	7.0
					6069.7	0.13	13.6

Table 7.6 Europium Pair Spectrometer Run 11221
GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 2

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
					6229.8	0.09	14.2
		1657.3	-90.9			0.22	
20	2497	315.4	2173.7	1129.2	6250.0	0.13	27.0
					6311.3	0.07	19.3
					6418.7	0.04	19.1
		493.4	-178.0			0.11	
21	2616	-8.2	1974.5	694.2	6500.0	-0.00	940.9
		276.2	-284.3			0.0	
22	2734	68.7	1692.1	843.4	6750.0	0.03	109.1
					6760.6	0.09	17.0
		308.9	-240.1			0.09	
23	2853	178.4	1163.7	1447.2	7000.0	0.08	42.3
		331.6	-153.1			0.0	
24	2972	325.9	1214.3	1786.8	7250.0	0.16	24.9
					7281.9	0.16	9.2
		463.9	-138.0			0.16	
25	3090	740.3	1195.5	1816.5	7500.0	0.38	11.2
		798.0	-57.7			0.0	
26	3209	-512.8	1071.9	-924.1	7750.0	-0.28	5.9
		57.0	-569.7			0.0	
27	3328	-43.1	249.8	-77.6	8000.0	-0.03	52.1
		58.0	-101.1			0.0	
28	3447	46.2	153.9	33.7	8250.0	0.03	49.4
		96.4	-50.1			0.0	
29	3565	-66.1	218.7	-97.6	8500.0	-0.05	30.5
		49.6	-115.7			0.0	
30	3684	6.2	174.9	-86.9	8750.0	0.00	326.2
		119.5	-113.3			0.0	
31	3803	-54.5	179.8	-94.8	9000.0	-0.05	33.1
		50.2	-104.7			0.0	
32	3921	53.1	39.4	-16.1	9250.0	-0.00	25.2
		92.9	-39.8			0.0	
33	4040	-7.0	20.5	-47.3	9500.0	-0.00	100.0
		17.9	-24.9			0.0	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 6294.80
UNRES = 79.1 -0.5 = 78.5%RES = 1.2%TOTAL = 79.7%
CS UNRES (EST) = 6.1% CS RES = 0.5% TOTAL ALL = 86.3%

NOTE: For shielding calculations, see Table 10.1 which normalizes the above results so that 100% of the average binding energy of the sample is observed.

Table 7.6 (Continued) Eu PS GAMABC Results

Table 7.7 Europium Comparison of Results

Strong Peaks Only, I > 0.04, I given in number of gamma rays of energy E emitted per 100 captures in the sample.

Present Work		MIT-NE-85 R-1	Nuclear Data Tables (ND-2) Shera A=152
Energy keV	semi I	semi I	semi I*
6418.7	0.04	0.03	
6311.3	0.07	0.03	0.023
6229.8	0.09	0.11	0.077
6069.7	0.13	0.08	0.110
5920.9	0.32**	0.14	0.092
5817.0		0.07	0.112
5597.7	0.04	0.03	0.075
5503.4	0.09	0.08	
4286.0	0.05	0.06	
458.4	0.18	0.12	
424.0	0.24	0.08	
389.5	0.18	0.10	
320.3	0.42	0.24	
302.1	0.41		Schult A=152
296.1	0.58	0.07	61Sc19
286.2	0.30	0.16	cryst
244.1	0.98	0.54	I*
233.5	0.21		
221.6	1.84	0.70	3.84
206.6	2.09	5.39	2.40
198.5	0.45		1.15
191.9	0.47		0.96
181.3	0.24		0.15

* Listed intensities multiplied by 0.96 from those in (ND-2)
** Iron capture peak interference at 5918 keV.

8. GADOLINIUM RESULTS

8.1 Gadolinium Sample

Table 8.1 lists the sample characteristics and run information for gadolinium. The sample consisted of 12.1 milligram of gadolinium oxide mixed with 1.0 grams of graphite powder (lampblack) in a poly vial of dimensions 3/4 inch diameter by 1 1/8 inches long. Gadolinium-157 contributes 81% of the captures in the sample while Gadolinium-155 gives 18% of the captures. The effective thermal neutron capture cross section for this sample is 48,100 barns, which was corrected by the Westcott factors to 31,200 barns. The average binding energy for the sample was 8038.1 keV, and the flux depression factor used was 0.83.

8.2 Gadolinium Compton Suppression Results

Figure 8.1 shows the gadolinium Compton suppression spectrum, run 11192. Tables 8.2 and 8.3 giv the GAMANL parameters and GAMANL results for this data. A total of 40 peaks were analysed and printed out, with 38 peaks being due to the gadolinium sample, and 2 peaks being background.

TABLE 8.1 GADOLIMIUM SAMPLE DATA AND RUN INFORMATION

Sample: Gd_2O_3 At. Wt.: 157.25

Wt.: 10.4 mg Gd Description: 12.1 mg Gd_2O_3 Mixed with 1.0 gram Lampblack in Poly Vial 3/4" diam x 1 1/8". Full Vial.

Holder: Al

	Gd^{155}	Gd^{157}
Isotope:		
Natural %:	14.73	15.68
Thermal Capture :	61000b	254000b
Percent Captures in Natural Mixture:	18	81
Binding Energy of Product Nucleus: keV	8527	7929

Effective Capture Cross Section: $\hat{\sigma} = 4.81 \times 10^4$ b

Westcott Correction: $\sigma_c = \hat{\sigma}(g + rs) = 4.81 \times 10^4(.660-.743(.017))$

$\sigma_c = 3.12 \times 10^4$ b

Average Binding Energy for Sample: 8038.1 keV

Flux Depression Factor: $F_1 = 0.83$ $N_T\sigma_c = 1.242$ cm^2 $\rho\bar{x} = 0.448$gm/cm^2

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	11192	11191
Computer Job No:	J40596	J50029
Average Thermal Flux: ϕ(n/cm^{2}sec)	$1.83 \times 10^{+8}$	$1.83 \times 10^{+8}$
Fraction of Sample Viewed by 1" Collimator: F_2	1.00	1.00
Collimator Used: Diam.	1/2"	1/2"
Duration of Run (Min):	210	1500
Dead Time Corrected Run Time: (Min) t	174.5	1500
SANGLE	1.58×10^{-5}	1.58×10^{-5}
FLUXT $= F_2N_T\sigma_c \frac{F_1\phi t}{100}$	$1.98 \times 10^{+10}$	$1.70 \times 10^{+11}$

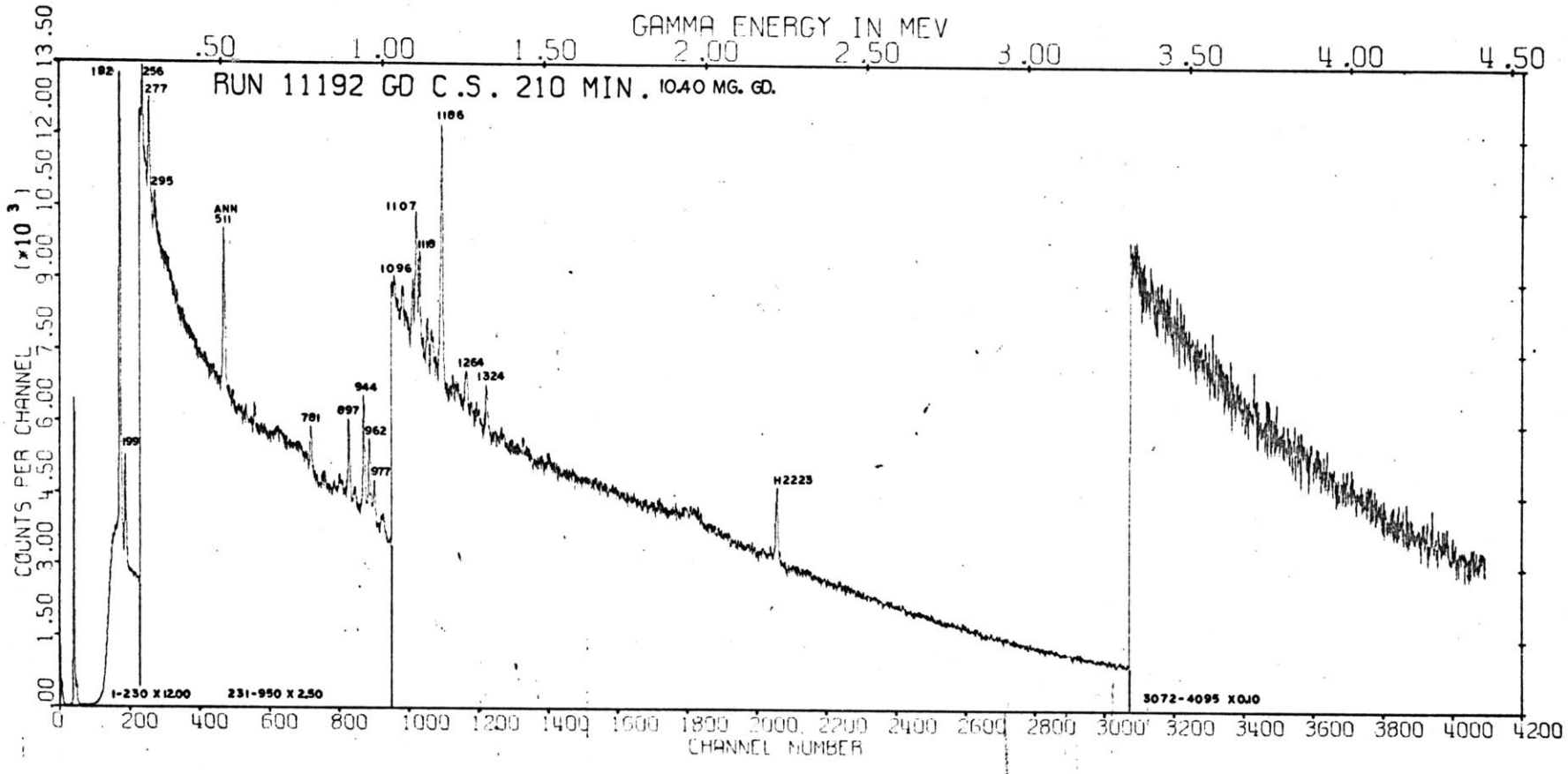

Figure 8.1 Gadolinium Compton Suppression Spectrum 11192

```
PARAMETERS AND INPUT DATA FOR RUN 11192  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  182
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   2.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  7.00 FWHM RANGE ERFW =  3.00
ENERGY PER CHANNEL NUMBER (KEV) = 1.079
CALIB1 E = 511.0 CNTR =  471 CORR = 469.4 FWHM =  6.14
CALIB2 E =2223.3 CNTR = 2058 CORR =2056.8 FWHM =  7.68
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.198E 11
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.437E-01 0.268E-01 0.181E-01 0.139E-01 0.113E-01
 0.103E-01 0.850E-02 0.725E-02 0.632E-02 0.563E-02
 0.494E-02 0.431E-02 0.383E-02 0.340E-02 0.302E-02
 0.254E-02 0.231E-02 0.210E-02 0.173E-02 0.158E-02
 0.136E-02 0.121E-02 0.104E-02 0.917E-03 0.838E-03
 0.746E-03 0.656E-03 0.596E-03
NUMBER OF PEAKS ANALYSED = 41   J40596
```

Table 8.2 Gadolinium Compton Suppression Run 11192
GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1Gd	199.4	188.5	25939.8	0.7069	141193.1	0.7	10.280	5.53	0.44E-01	14.	S *
					144583.2	0.8	10.527	5.51			
2Gd	230.7	216.5	830.2	0.0255	4061.0	14.2	0.319	5.42	0.41E-01	9.	S *
					4656.7	15.8	0.366	5.54			
3Gd	239.3	224.2	836.5	0.0263	2736.6	17.0	0.219	3.56	0.40E-01	7.	S *
					4700.7	15.5	0.377	5.55			
4Gd	255.6	238.9	3148.6	0.1052	15829.8	6.2	1.321	4.99	0.38E-01	18.	S *
					17751.4	4.3	1.482	5.57			
5Gd	276.9	258.0	4740.3	0.1768	28798.9	3.0	2.533	5.73	0.36E-01	16.	S *
					26839.2	2.8	2.360	5.60			
6Gd	294.9	274.2	1562.1	0.0622	10397.4	7.8	0.956	6.04	0.35E-01	16.	S *
					8876.7	7.6	0.816	5.62			
7Gd	363.6	336.5	540.3	0.0257	1817.9	20.8	0.198	3.67	0.29E-01	7.	S *
					3112.7	19.4	0.339	5.69			
8Gd	381.0	352.3	634.1	0.0314	2048.0	18.2	0.233	3.52	0.28E-01	7.	S *
					3665.0	16.3	0.416	5.71			
B 9An	511.0	471.0	8101.9	0.4853	52254.4	1.7	7.775	6.13	0.21E-01	21.	S *
					48024.5	1.6	7.146	5.86			
10Gd	538.7	496.5	792.2	0.0500	2914.0	12.6	0.458	3.95	0.20E-01	8.	S *
					4720.6	11.8	0.741	5.89			
11Gd	580.5	534.9	519.2	0.0343	2127.4	20.0	0.362	4.08	0.19E-01	10.	S *
					3118.4	17.3	0.530	5.94			
12Gd	607.4	559.6	973.0	0.0661	4359.7	10.5	0.775	4.66	0.18E-01	11.	S *
					5873.3	9.4	1.045	5.97			
13Gd	625.6	576.4	466.9	0.0325	1585.9	19.8	0.289	3.69	0.17E-01	7.	S *
					2828.2	18.7	0.516	5.99			
14Gd	780.7	719.7	2401.9	0.1946	16270.0	4.3	3.642	6.17	0.14E-01	20.	S *
					14968.6	3.9	3.350	6.16			
15Gd	816.6	753.0	535.7	0.0463	2814.4	11.3	0.658	6.20	0.14E-01	16.	D .049
					3361.8	14.8	0.786	6.20			

Table 8.3 Gadolinium Compton Suppression Run 11192 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE	
					AREA-G	ERR-G	INT-G	FWHM-C				
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
16	Gd 822.8	758.8	612.7	0.0529	3201.2	11.3	0.754	6.20	0.14E-01	16.	D	.049
					3845.2	13.1	0.906	6.20				
17	Gd 851.4	785.2	448.1	0.0396	2190.2	15.5	0.534	5.37	0.13E-01	9.	S	*
					2828.4	17.4	0.689	6.24				
18	Gd 868.8	801.4	789.7	0.0701	4446.6	9.0	1.105	6.26	0.13E-01	17.	D	.005
					5003.2	10.2	1.243	6.26				
19	Gd 876.6	808.6	610.1	0.0541	3452.5	9.0	0.865	6.26	0.13E-01	17.	D	.005
					3865.3	13.0	0.969	6.26				
20	Gd 897.3	827.7	4196.9	0.3797	27519.5	2.2	7.051	6.53	0.12E-01	18.	S	*
					26705.1	2.4	6.843	6.29				
21	Gd 916.6	845.6	793.4	0.0743	5986.0	8.4	1.565	8.06	0.12E-01	15.	S	*
					5065.6	9.9	1.324	6.31				
NUMBER OF MAXIMA IN MULTIPLET = 4												
THE 3 STRONGEST PEAKS ARE ANALYSED AS A TRIPLET.												
22	Gd 944.0	870.9	6078.4	0.6162	42584.7	2.0	11.435	6.36	0.12E-01	48.	T	.000 .000
					39114.0	1.8	10.503	6.36				
23	Gd 961.8	887.4	4249.2	0.4307	29425.2	2.0	8.033	6.36	0.12E-01	48.	T	.000 .000
					27343.0	2.3	7.464	6.36				
24	Gd 977.2	901.6	2336.4	0.2368	16176.9	2.0	4.476	6.36	0.12E-01	48.	T	.000 .000
					15034.2	3.7	4.160	6.36				
25	Gd 988.5	912.1	356.4	0.0381	1203.0	21.8	0.336	3.70	0.11E-01	6.	S	
					2304.3	19.9	0.644	6.39				
26	Gd 999.1	921.9	817.3	0.0910	6199.5	6.5	1.747	6.41	0.11E-01	23.	D	.140
					5296.6	8.9	1.493	6.41				
27	Gd1004.9	927.2	881.0	0.0981	6672.9	6.5	1.884	6.41	0.11E-01	23.	D	.140
					5709.7	8.3	1.612	6.41				
28	Gd1040.1	960.1	383.0	0.0443	1429.2	18.9	0.408	4.01	0.11E-01	8.	S	*
					2498.3	17.9	0.713	6.45				
29	Gd1065.2	983.4	598.6	0.0729	3710.2	10.6	1.069	6.43	0.11E-01	13.	S	*
					3921.9	11.5	1.130	6.48				
30	Gd1096.4	1012.3	1108.7	0.1446	6820.6	3.2	1.991	6.52	0.11E-01	34.	T	.001 .001
					7316.2	6.3	2.135	6.52				

Table 8.3 (Continued) Gd CS

PEAK ANALYSIS PAGE 3

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S / AREA-G	ERR-S / ERR-G	INT-S / INT-G	FWHM-M / FWHM-C	EFF(E)	BASE	TYPE		
	KEV	CH NC	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN			
31	Gd1	107.3	1022.3	2682.6	0.3499	16503.1	3.2	4.841	6.52	0.11E-01	34.	T	.001	.001
						17702.3	3.0	5.193	6.52					
32	Gd1	118.4	1032.4	1954.7	0.2550	11923.9	3.2	3.517	6.52	0.11E-01	34.	T	.001	.001
						12898.9	3.9	3.804	6.52					
33	Gd1	142.4	1054.5	871.7	0.1208	5469.0	6.8	1.633	6.63	0.11E-01	13.	S	*	
						5786.0	7.7	1.728	6.56					
34	Gd1	154.2	1065.3	773.9	0.1089	6325.1	8.0	1.901	9.57	0.11E-01	15.	S		
						5147.0	8.5	1.547	6.57					
35	Gd1	186.5	1095.1	5267.5	0.7654	38250.8	1.5	11.728	6.97	0.10E-01	22.	S	*	
						35223.5	1.8	10.800	6.61					
36	Gd1	220.3	1126.4	369.7	0.0562	1670.1	15.6	0.527	4.97	0.10E-01	9.	S	*	
						2486.0	16.4	0.785	6.65					
37	Gd1	263.6	1166.6	758.8	0.1206	6544.8	8.2	2.157	9.36	0.97E-02	17.	S		
						5139.6	8.2	1.694	6.70					
38	Gd1	324.4	1223.2	992.5	0.1736	8403.8	6.4	2.938	7.62	0.91E-02	23.	S	*	
						6789.6	6.3	2.373	6.76					
39	Gd1	438.5	1328.7	315.0	0.0589	1222.8	17.5	0.473	4.20	0.82E-02	8.	S	*	
						2194.5	17.4	0.849	6.89					
B 40	H	2223.3	2057.1	1424.1	0.4519	11443.1	3.6	7.504	7.68	0.49E-02	23.	S	*	
						11155.2	6.2	7.316	7.74					

Table 8.3 (Continued) Gd CS

8.3 Gadolinium Pair Spectrometer Results

Figure 8.2 shows the gadolinium pair spectrometer spectrum, run 11191. The spectrum shows a few strong well resolved gamma lines above 5.0 MeV. A large unresolved continuum portion of the spectrum extends from 1.5 MeV to 5.0 MeV.

Table 8.4 gives the GAMANL and GAMABC parameters for this data. Tables 8.5 and 8.6 present the GAMANL results and the GAMABC results. A total of 84 peaks were analysed with 74 being printed out. Of these, 56 are capture gammas from gadolinium, 8 are marginal peaks (tentatively assigned to gadolinium), and 10 are background peaks.

The GAMABC results of analysing the continuum show a large unresolved region from 1.7 MeV to 4.5 MeV, as indicated by the large intensity per energy bin width of 250 keV in Table 8.6. The threshold setting and low energy raise of the analyser introduces perturbations in the result for the first bin, and this result should be disregarded.

The total percent fraction of the average binding energy of the sample seen is 107.6%. Of this, 19.8% is from the resolved lines of gadolinium, and 87.8% is from the unresolved capture gammas in the continuum. This 87.8% is divided into 77.0% being due to the continuum above 2.0 MeV, and 10.8% estimated as being from the continuum below 2.0MeV.

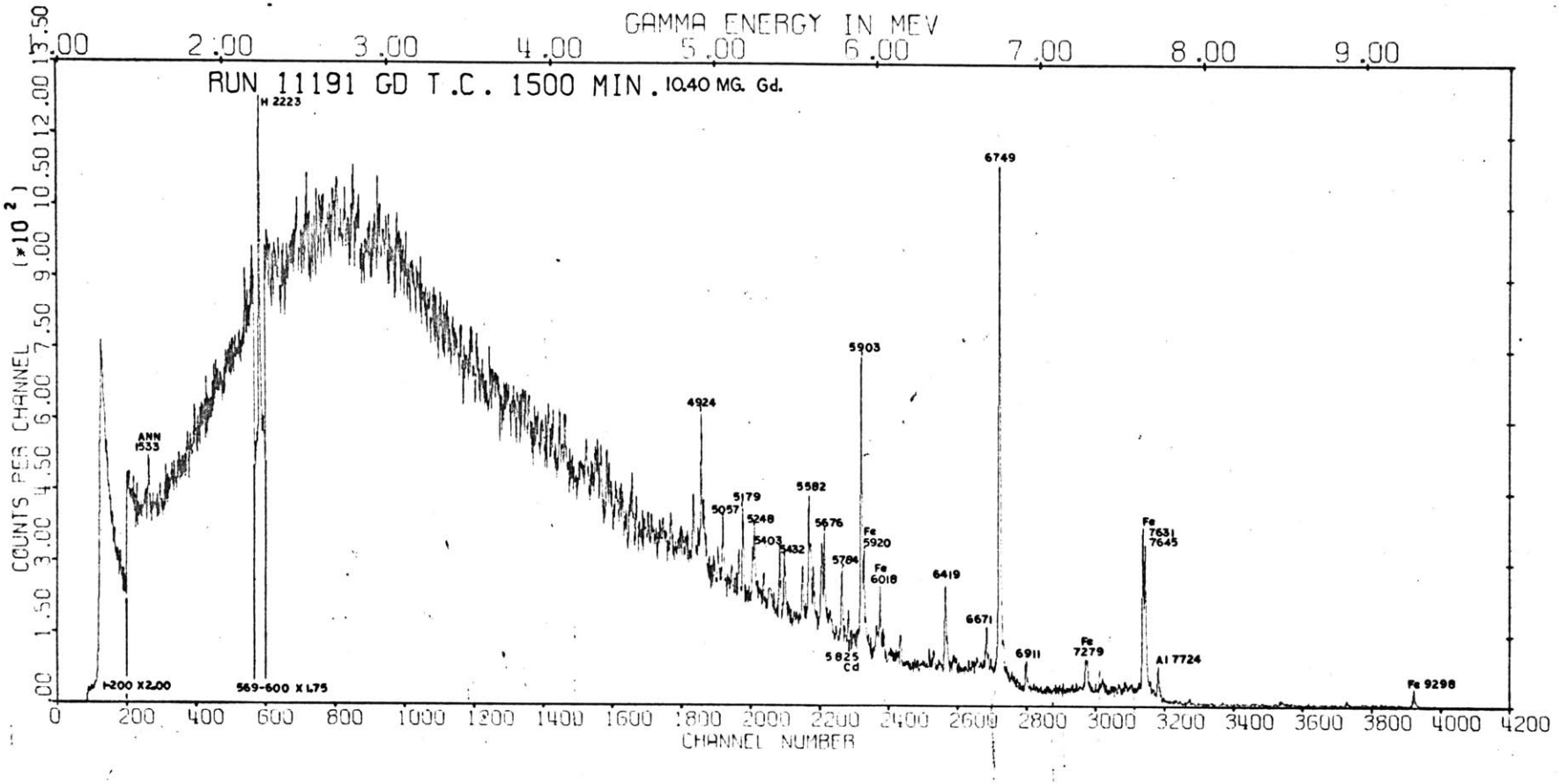

Figure 8.2 Gadolinium Pair Spectrometer Spectrum 11191

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PARAMETERS AND INPUT DATA FOR RUN 11191  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  223
BACKGROUND CRITERION BCR * SQRT(BK) BCR =   3.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   2.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  8.00 FWHM RANGE ERFW =  3.50
ENERGY PER CHANNEL NUMBER (KEV) = 2.118
CALIB1 E =2223.3 CNTR =  584 CORR = 583.8 FWHM =  8.95
CALIB2 E =7723.8 CNTR = 3182 CORR =3180.8 FWHM =  7.29
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.170E 12
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.100E-06 0.101E-03 0.259E-03 0.422E-03 0.591E-03
 0.742E-03 0.864E-03 0.906E-03 0.931E-03 0.927E-03
 0.915E-03 0.875E-03 0.813E-03 0.723E-03 0.637E-03
 0.550E-03 0.458E-03 0.369E-03 0.281E-03
NUMBER OF PEAKS ANALYSED = 87    J50029

GAMABC PEAKS RESPONSE FUNCTION PARAMETERS
F2 = 0.00085 x AREA        F5 = 0.00160 x AREA
F3 = 0.00045 x AREA        F8 = 0.00512 x AREA
LOW CH = IMAX              MID CH = 900
W1 = 120 + 130 (E - 2200)/4610  for E ≤ 6810 keV
W1 = 250 + 125 (E - 6800)/ 450  for E > 6810 keV
W2 = 0.0004 x AREA + 2.0
W3 = 70
BAKFAC = 1.350   BIN WIDTH = 10 CHS   RED = 1.0512
```

Table 8.4 Gadolinium Pair Spectrometer Run 11191
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/10CC	KEV	N/CTS	CHAN	
B	1An	1534.0	263.7	107.6	0.2579	452.7	18.6	1.505	8.42	0.11E-03	12.	S *
						450.5	16.7	1.498	8.28			
	2Gd	1777.2	375.3	68.2	0.1370	372.7	23.2	0.734	12.12	0.19E-03	9.	S
						289.3	26.1	0.570	8.38			
	3Gd	2135.6	543.0	139.1	0.1779	425.6	17.7	0.521	6.28	0.30E-03	7.	S *
						598.9	16.6	0.733	8.52			
B	4H	2223.3	584.2	1267.7	1.2768	5857.2	2.8	6.555	8.95	0.33E-03	14.	S *
						5478.2	3.6	6.131	8.55			
	5Gd	2291.1	616.1	103.3	0.1193	481.7	18.1	0.505	10.06	0.35E-03	8.	S *
						447.4	22.4	0.469	8.57			
	6Gd	2344.6	641.1	90.6	0.1030	334.0	23.6	0.334	7.69	0.37E-03	7.	S *
						393.2	25.4	0.393	8.58			
	7Gd	2515.3	721.7	95.1	0.0975	321.7	28.5	0.279	5.71	0.43E-03	8.	S *
						415.0	25.4	0.360	8.63			
	8Gd	2534.1	730.6	93.6	0.1020	213.3	29.3	0.182	4.69	0.43E-03	5.	S *
						408.8	25.1	0.349	8.64			
	9Gd	2577.3	751.0	104.8	0.1108	324.7	22.5	0.268	6.60	0.45E-03	6.	S *
						458.3	22.9	0.378	8.65			
	10Gd	2597.1	760.3	97.1	0.1002	381.4	24.0	0.310	8.30	0.46E-03	8.	S *
						424.9	24.8	0.345	8.66			
	11Gd	2700.9	809.1	125.4	0.1277	720.4	18.4	0.543	12.47	0.49E-03	10.	S
						550.6	19.8	0.415	8.68			
	12Gd	2750.7	832.6	91.6	0.0948	397.2	23.1	0.290	10.55	0.51E-03	8.	S *
						402.9	26.1	0.294	8.70			
	13Gd	2799.1	855.5	128.9	0.1304	549.9	15.4	0.388	9.60	0.53E-03	7.	S *
						567.6	19.3	0.401	8.71			
	14Gd	2901.3	903.8	92.1	0.0991	252.5	28.5	0.168	5.87	0.56E-03	6.	S *
						406.5	25.6	0.270	8.73			
	15Gd	3001.9	951.2	98.2	0.1063	434.0	22.6	0.272	10.11	0.59E-03	9.	S *
						434.5	24.1	0.273	8.75			

Table 8.5 Gadolinium Pair Spectrometer Run 11191 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/1CCC	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
16Gd	3451.1	1163.2	87.3	0.1237	379.7	20.8	0.193	10.09	0.73E-03	8.	S *
					389.4	24.0	0.198	8.82			
17Gd	3549.9	1209.8	95.0	0.1380	311.6	22.5	0.153	7.05	0.76E-03	7.	S *
					424.4	22.0	0.208	8.84			
18 Gd	3849.4	1351.0	82.6	0.1416	245.4	29.0	0.109	6.01	0.84E-03	8.	S *
					370.2	23.4	0.164	8.86			
19 Gd	3871.8	1361.6	81.1	0.1403	375.8	19.1	0.166	10.24	0.84E-03	8.	S *
					363.5	23.7	0.161	8.86			
20 Gd	3972.7	1409.3	82.6	0.1590	184.0	29.5	0.079	4.67	0.86E-03	5.	S
					370.4	22.3	0.160	8.87			
21 Gd	3988.9	1416.9	91.5	0.1715	502.2	15.2	0.216	12.05	0.86E-03	9.	S *
					410.5	20.6	0.177	8.87			
22 Gd	4058.4	1449.7	89.0	0.1691	372.5	20.1	0.159	9.95	0.87E-03	9.	S *
					399.2	21.0	0.170	8.87			
23 Gd	4089.1	1464.2	107.2	0.2113	560.5	15.5	0.238	10.91	0.87E-03	11.	S *
					480.8	17.7	0.204	8.87			
24 Gd	4220.4	1526.1	97.1	0.2062	658.7	15.4	0.276	12.32	0.88E-03	14.	S *
					435.8	18.7	0.183	8.87			
25x	4276.0	1552.1	55.9	0.1162	217.9	26.9	0.091	8.45	0.89E-03	7.	S *
					250.9	30.7	0.105	8.87			
26 Gd	4292.7	1560.0	67.0	0.1420	232.0	25.1	0.097	7.29	0.89E-03	7.	S *
					300.7	25.9	0.125	8.87			
27 Gd	4346.5	1585.5	124.6	0.2957	526.5	14.1	0.218	9.10	0.89E-03	10.	S *
					559.1	14.7	0.232	8.87			
28x	4426.4	1623.5	51.9	0.1289	221.5	24.3	0.091	9.52	0.90E-03	7.	S *
					232.8	30.5	0.096	8.87			
29 Gd	4482.0	1649.8	68.7	0.1874	240.7	13.3	0.099	8.87	0.90E-03	14.	T .080 .080
					308.2	23.0	0.126	8.87			
30 Gd	4490.7	1653.9	66.9	0.1823	236.9	13.3	0.097	8.87	0.91E-03	14.	T .080 .080
					299.8	23.6	0.123	8.87			
31 Gd	4500.2	1658.4	103.3	0.2816	349.3	13.3	0.143	8.87	0.91E-03	14.	T .080 .080
					463.3	16.3	0.190	8.87			

Table 8.5 (Continued) Gd PS

PEAK ANALYSIS PAGE 3

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100	KEV	N/CTS	CHAN		
32	Gd4526.5	1670.9	83.8	0.2448	409.3	16.2	0.167	10.43	0.91E-03	10.	S	*
					375.9	19.0	0.154	8.87				
33	Gd4600.6	1705.8	61.4	0.1740	216.0	28.2	0.088	6.81	0.91E-03	9.	S	*
					275.3	25.0	0.112	8.86				
34	Gd4737.6	1770.6	66.8	0.1999	300.0	20.0	0.121	10.03	0.92E-03	9.	S	*
					299.2	22.8	0.120	8.85				
35	Gd4875.9	1835.9	129.1	0.3984	643.7	11.8	0.257	9.58	0.93E-03	12.	S	*
					576.9	13.2	0.231	8.84				
36	Gd4924.3	1858.8	234.0	0.6364	871.2	7.7	0.348	7.76	0.93E-03	9.	S	*
					1045.4	8.7	0.417	8.83				
37	Gd4939.4	1865.9	65.0	0.1767	250.2	22.9	0.100	7.43	0.93E-03	8.	S	*
					290.5	24.2	0.116	8.83				
38	x 5025.8	1906.7	57.0	0.2027	140.0	25.3	0.056	5.18	0.93E-03	5.	S	*
					254.4	24.5	0.101	8.82				
39	Gd5057.1	1921.5	133.5	0.5007	596.0	10.2	0.237	9.07	0.93E-03	10.	S	*
					595.2	12.2	0.237	8.82				
40	x 5110.1	1946.7	50.7	0.2001	164.3	26.1	0.065	6.89	0.93E-03	7.	S	*
					226.0	26.1	0.090	8.81				
41	Gd5155.7	1968.3	87.1	0.3558	369.6	14.3	0.147	9.11	0.93E-03	9.	S	*
					387.7	16.5	0.155	8.80				
42	Gd5178.7	1979.1	166.2	0.7156	885.7	9.0	0.353	11.76	0.93E-03	12.	S	
					739.6	10.1	0.295	8.80				
43	Gd5237.7	2007.1	91.5	0.3788	386.6	10.2	0.154	8.79	0.93E-03	15.	D	.018
					406.7	15.8	0.162	8.79				
44	Gd5248.2	2012.1	131.4	0.5439	555.8	10.2	0.222	8.79	0.93E-03	15.	D	.018
					583.9	12.0	0.233	8.79				
45	Gd5305.2	2039.0	60.2	0.2654	174.1	25.8	0.069	6.01	0.93E-03	8.	S	*
					267.1	21.7	0.107	8.78				
46	Gd5402.6	2085.1	138.1	0.7186	698.9	9.7	0.279	8.88	0.93E-03	14.	S	*
					611.7	11.0	0.244	8.76				
47	x 5431.7	2098.9	101.4	0.4976	593.5	12.3	0.237	12.29	0.93E-03	12.	S	
					448.8	14.0	0.179	8.75				

Table 8.5 (Continued) Gd PS

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE
						AREA-G	ERR-G	INT-G	FWHM-C			
		KEV	CH NC	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
	48Gd	5543.3	2151.5	115.4	0.6036	536.6	10.4	0.215	9.46	0.93E-03	11.	S *
						509.7	12.5	0.204	8.73			
	49Gd	5582.3	2169.9	208.6	0.9741	833.0	6.3	0.333	8.72	0.93E-03	13.	D .073
						919.8	8.5	0.368	8.72			
	50Gd	5591.6	2174.2	125.0	0.5837	497.8	6.3	0.199	8.72	0.93E-03	13.	D .073
						551.1	12.1	0.221	8.72			
	51Gd	5609.1	2182.5	93.9	0.4468	366.0	13.5	0.147	7.37	0.93E-03	9.	S *
						413.8	14.9	0.166	8.72			
	52Gd	5661.0	2207.2	166.8	0.9344	848.5	7.4	0.340	8.70	0.93E-03	24.	D .000
						734.0	9.6	0.294	8.70			
	53Gd	5676.1	2214.4	178.5	0.9998	882.2	7.4	0.354	8.70	0.93E-03	24.	D .000
						785.3	9.1	0.315	8.70			
	54Gd	5784.4	2265.6	136.1	0.8808	630.2	8.3	0.253	8.96	0.92E-03	11.	S *
						596.7	10.7	0.240	8.67			
B	55Cd	5824.5	2284.5	54.6	0.3758	231.0	17.5	0.093	8.08	0.92E-03	9.	S *
						239.2	20.5	0.096	8.66			
	56Gd	5902.8	2321.6	595.8	3.4204	2540.4	3.4	1.025	8.64	0.92E-03	18.	D .000
						2603.1	4.4	1.051	8.64			
B	57Fe	5919.8	2329.7	146.6	0.8416	624.6	3.4	0.252	8.64	0.92E-03	18.	D .000
						640.5	10.4	0.259	8.64			
	58Gd	5994.6	2365.1	36.1	0.2564	95.3	30.0	0.039	5.63	0.92E-03	6.	S *
						157.4	28.2	0.064	8.62			
B	59Fe	6017.8	2376.0	109.4	0.7624	424.4	10.0	0.172	7.54	0.91E-03	9.	S *
						476.4	12.2	0.193	8.61			
	60Gd	6142.7	2435.1	60.4	0.6061	245.0	13.1	0.100	8.68	0.91E-03	8.	S *
						262.0	17.2	0.107	8.57			
	61Gd	6319.6	2518.8	32.3	0.3792	69.3	28.6	0.029	4.54	0.89E-03	5.	S *
						139.0	26.4	0.058	8.51			
	62x	6347.3	2531.9	31.9	0.3586	150.4	24.5	0.063	10.25	0.89E-03	9.	S
						137.3	26.9	0.057	8.50			
	63Gd	6418.8	2565.9	177.1	2.0519	853.2	6.0	0.359	8.47	0.88E-03	16.	D .013
						758.9	8.3	0.319	8.47			

Table 8.5 (Continued) Gd PS

PEAK ANALYSIS PAGE 5

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
64	Gd6428.9	2570.6	53.2	0.6170	251.3	6.0	0.106	8.47	0.88E-03	16.	D	.013
					228.2	18.2	0.096	8.47				
65	Gd6671.3	2685.1	78.8	0.7997	303.7	11.6	0.132	6.62	0.86E-03	9.	S	*
					334.0	14.2	0.145	8.38				
66	Gd6748.7	2721.6	1060.8	9.3256	5557.7	1.8	2.433	9.14	0.85E-03	20.	S	*
					4478.4	3.2	1.961	8.35				
67	Gd6911.0	2798.3	50.4	1.2971	314.1	11.8	0.141	12.30	0.83E-03	14.	S	
					210.9	16.3	0.095	8.28				
68	x 7139.9	2906.2	21.7	0.7124	44.4	24.5	0.021	4.37	0.79E-03	4.	S	*
					89.9	27.0	0.042	8.17				
B 69	Fe7278.7	2971.9	54.9	1.1158	235.9	9.4	0.115	8.10	0.76E-03	13.	D	.048
					225.0	16.0	0.110	8.10				
70	x 7286.7	2975.7	45.8	0.9317	194.2	9.4	0.095	8.10	0.76E-03	13.	D	.048
					187.8	18.0	0.092	8.10				
B 71	Fe7629.6	3137.3	336.6	7.2390	1705.3	2.5	0.903	7.91	0.70E-03	22.	D	.000
					1347.3	5.9	0.713	7.91				
B 72	Fe7643.7	3144.0	275.8	5.9310	1421.9	2.5	0.756	7.91	0.70E-03	22.	D	.000
					1103.9	6.5	0.587	7.91				
B 73	Al7723.8	3181.9	51.3	1.4241	192.2	11.0	0.104	7.29	0.68E-03	8.	S	*
					203.9	16.1	0.111	7.86				
B 74	Fe9297.6	3922.3	23.7	1.5823	58.0	17.1	0.053	5.14	0.41E-03	5.	S	*
					80.8	27.2	0.074	6.75				

Table 8.5 (Continued) Gd PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	243	-3036.4	8780.1	39799.0	1500.0	-8.04	10.4
		186.5	-3222.9			0.0	
2	361	6635.1	9395.7	53500.6	1750.0	11.21	5.5
					1777.2	0.73	23.2
		6779.0	-143.9			0.73	
3	479	20323.2	10396.1	65319.6	2000.0	25.16	2.0
					2135.6	0.52	17.7
		20323.2	0.0			0.52	
4	597	28899.3	11269.0	69109.6	2250.0	28.40	1.5
					2291.1	0.51	18.1
					2344.6	0.33	23.6
		28899.3	0.0			0.84	
5	715	34108.9	11923.6	69435.6	2500.0	27.15	1.3
					2515.3	0.28	28.5
					2534.1	0.18	29.3
					2577.3	0.27	22.5
					2597.1	0.31	24.0
					2700.9	0.54	18.4
		34108.9	0.0			1.58	
6	833	36481.5	11746.0	66469.6	2750.0	24.68	1.2
					2750.7	0.29	23.1
					2799.1	0.39	15.4
					2901.3	0.17	28.5
		36481.5	0.0			0.85	
7	951	34628.9	11446.1	60892.8	3000.0	20.35	1.2
					3001.9	0.27	22.6
		34628.9	0.0			0.27	
8	1070	27748.6	10930.6	51813.1	3250.0	14.73	1.4
					3451.1	0.19	20.8
		27748.6	0.0			0.19	
9	1188	24289.4	9883.0	44708.6	3500.0	11.55	1.5
					3549.9	0.15	22.5
		24289.4	0.0			0.15	
10	1306	20441.6	9307.6	38676.6	3750.0	8.91	1.7
					3849.4	0.11	29.0
					3871.8	0.17	19.1
					3972.7	0.08	29.5
					3988.9	0.22	15.2
		20441.6	0.0			0.57	
11	1424	16916.5	8647.0	32956.8	4000.0	7.17	1.9
					4058.4	0.16	20.1
					4089.1	0.24	15.5
		16916.5	0.0			0.40	
12	1542	14301.1	7949.8	27585.9	4250.0	5.93	2.0
					4276.0	0.09	26.9

Table 8.6 Gadolinium Pair Spectrometer Run 11191
GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 25C.0 KEV PAGE 2

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR CCLNTS	ENERGY KEV	INT N/100C	ERR PCSD
					4292.7	C.1C	25.1
					4346.5	0.22	14.1
					4426.4	C.09	24.3
					4482.0	C.1C	13.3
					4490.7	0.10	13.3
		14301.1	0.0			0.69	
13	1660	11284.4	6926.9	23412.1	4500.0	4.58	2.4
					4500.2	0.14	13.3
					4526.5	C.17	16.2
					4600.6	0.09	28.2
					4737.6	0.12	20.0
		11284.4	0.0			0.52	
14	1778	11529.8	6224.5	20719.8	4750.0	4.60	2.2
					4875.9	0.26	11.8
					4924.3	C.35	7.7
					4939.4	0.10	22.9
		11529.8	0.0			0.71	
15	1896	6980.9	5923.2	16422.7	5000.0	2.78	3.3
					5025.8	0.06	25.3
					5057.1	C.24	10.2
					5110.1	0.07	26.1
					5155.7	0.15	14.3
					5178.7	C.35	9.C
					5237.7	0.15	10.2
					5248.2	C.22	10.2
		6980.9	0.0			1.23	
16	2014	5674.6	5248.4	13807.0	5250.0	2.27	3.7
					5305.2	C.07	25.8
					5402.6	C.28	9.7
					5431.7	0.24	12.3
		5674.6	0.0			0.59	
17	2132	5192.5	4364.4	12247.2	5500.0	2.08	3.8
					5543.3	0.21	10.4
					5582.3	C.33	6.3
					5591.6	0.20	6.3
					5609.1	0.15	13.5
					5661.0	C.34	7.4
					5676.1	0.35	7.4
		5192.5	0.0			1.59	
18	2250	3728.0	3811.3	9296.3	5750.0	1.50	4.6
					5784.4	0.25	8.3
					5902.8	1.C3	3.4
					5994.6	0.04	30.0
		3757.3	-29.3			1.32	
19	2368	2623.6	3483.6	5886.1	6000.0	1.07	5.6
					6142.7	0.10	13.1

Table 8.6 (Continued) Gd PS GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 3

BIN NO	L CH NC	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/1CCC	ERR PC SD
		2664.1	-40.5			0.10	
20	2486	1592.7	2698.2	5656.9	6250.0	0.67	8.5
					6319.6	0.03	28.6
					6347.3	0.06	24.5
					6418.8	0.36	6.0
					6428.9	0.11	6.0
		1605.9	-13.2			0.56	
21	2604	1613.4	2422.4	5764.8	6500.0	0.69	8.3
					6671.3	0.13	11.6
					6748.7	2.43	1.8
		1682.2	-68.7			2.56	
22	2722	933.7	2150.4	2819.9	6750.0	0.41	11.4
					6911.0	0.14	11.8
		1191.4	-257.7			0.14	
23	2840	171.9	1445.4	1816.5	7000.0	0.08	49.0
					7139.9	0.02	24.5
		373.5	-201.6			0.02	
24	2958	494.7	1382.6	2081.7	7250.0	0.25	17.9
					7286.7	0.09	9.4
		697.1	-202.4			0.09	
25	3076	831.2	1237.6	2121.3	7500.0	0.44	10.5
		871.2	-40.0			0.0	
26	3194	-745.8	1396.4	-1315.1	7750.0	-0.42	4.2
		32.1	-777.9			0.0	
27	3312	-149.6	403.9	-262.1	8000.0	-0.09	15.9
		65.5	-215.0			0.0	
28	3430	83.0	187.0	65.3	8250.0	0.05	32.1
		144.4	-61.4			0.0	
29	3548	-42.9	236.9	-78.5	8500.0	-0.03	52.5
		74.4	-117.3			0.0	
30	3666	23.2	183.4	-48.1	8750.0	0.02	95.6
		122.7	-99.5			0.0	
31	3784	-80.1	242.9	-204.8	9000.0	-0.07	22.4
		83.2	-163.3			0.0	
32	3902	47.7	120.4	-81.7	9250.0	-0.00	34.9
		123.6	-75.9			0.0	
33	4020	19.3	3.8	-49.1	9500.0	0.00	100.0
		48.8	-29.5			0.0	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 8038.10
UNRES = 80.2 -2.2 = 78.0% RES = 9.3% TOTAL = 87.3%
CS UNRES (EST) = 9.8% CS RES = 10.5% TOTAL ALL = 107.6%

NOTE: For shielding calculations, see Table 10.1 which normalizes the above results so that 100% of the average binding energy of the sample is observed.

Table 8.6 (Continued) Gd PS GAMABC Results

8.4 Gadolinium Comparison of Results

Table 8.7 shows a comparison of the results of this work with the published data for the intensities of the strong capture lines of gadolinium. The energies of the gamma lines as found in this work are also given. The main source of published listing of these intensities is Nuclear Data (ND-2). The results agree quite well with the data by Groshev, and are slightly higher than the values in MITNE-85 (R-1).

Table 8.7 Gadolinium Comparison of Results

Strong Peaks Only, I > 0.10 for E > 3.0MeV, I > 0.30 for E ≤ 3.0 MeV, I given in number of gamma rays of energy E emitted per 100 captures in the Gadolinium sample.

Present Work		MIT-NE-85	Nuclear Data Tables (ND-2)	
			Groshev	Knowles
			A = 158	A = 158
		R-1	62Gr33	60Knl
Energy	semi	semi	s Cp	s pr, cryst
keV	I	I	I*	I*
6911.0	0.14	0.07	0.097	0.04
6748.7	2.43	1.32	1.5	1.20
6671.7	0.13	0.08	0.13	
6428.9	0.11			
6418.8	0.36	0.22	0.23	0.16
6142.7	0.10	0.06	0.098	0.097
5902.8	1.02	0.47	0.86	0.60
5784.4	0.25	0.13	0.14	
5676.1	0.35	0.09	0.25	0.27
5661.0	0.34	0.15	0.26	
5609.1	0.15	0.07	0.16	
5591.6	0.20			
5582.3	0.33	0.24	0.40	0.36
5543.3	0.21	0.10	0.16	
5402.6	0.28	0.20	0.21	
5248.2	0.22	0.05	0.17	0.22
5237.7	0.15		0.18	
5178.7	0.35	0.19	0.23	0.19
5155.7	0.15	0.08	0.13	
5057.1	0.24	0.13	0.19	0.11
4924.3	0.35	0.19	0.46	
4875.9	0.26	0.09	0.36	
4737.6	0.12	0.16	0.11	
4526.5	0.17			
4500.2	0.14			
4346.5	0.22	0.15	0.25	
4220.4	0.28	0.04		
4089.1	0.24	0.04		
4958.4	0.16	0.13		
3988.9	0.22	0.04		
3871.8	0.17	0.04		
3549.9	0.15			
3451.1	0.19			
3001.9	0.27	0.17		
2799.1	0.39	0.26	0.16	
2700.9	0.54	0.22	0.16	
2597.1	0.31	0.26	0.24	
2344.6	0.33	0.10		0.04
2291.1	0.51		0.24	0.11

* Listed intensities multiplied by 0.81 from those in (ND-2)

Table 8.7 (Continued) Gadolinium Comparison of Results

Present Work		MIT-NE-85	62Gr23 A=158 s Cp	60Knl A=158 cryst	60Knl A=156 cryst	62Gr33 A=156 s Cp
Energy keV	semi I	semi I	I*	I*	I**	I**
2135.6	0.52	0.12	0.16	0.08		
1777.2	0.73	0.25				
1438.5	0.47		1.05	0.09		
1324.4	2.94	1.55	3.80	0.52		
1263.6	2.16	1.16	4.05	0.24		
1220.3	0.53		0.97	0.13		
1186.5	11.73	5.93	11.7	2.80	0.27	1.35
1154.2	1.90	0.25		0.04	0.54	3.17
1142.4	1.63	0.76	2.6	0.36		
1118.4	3.52	1.30	4.6	1.05		
1107.3	4.84	1.47	5.9	0.98		
1096.4	1.99	1.11	2.1	0.97		
1065.2	1.07	0.38		0.098	0.30	1.43
1040.1	0.41	0.36			0.15	0.68
1004.9	1.88	2.12	1.45			
999.1	1.75		1.45	0.28		
988.5	0.34	0.18	0.6	0.24		
977.2	4.48	1.35	4.6	0.56		
961.8	8.03	3.08	6.2	0.98		
944.0	11.44	4.24	9.7	3.4		
916.6	1.56	1.04	2.0	0.40		
897.3	7.05	2.82	7.4	1.86		
876.6	0.86		1.6	0.49		
868.8	1.10	0.34				
851.4	0.53	0.21	0.97	0.32		
822.8	0.75		0.98	0.32		
816.6	0.66					
780.7	3.64	1.69	3.64			
607.4	0.78	0.18		0.04		
580.5	0.36					Schult
538.7	0.46	0.16		0.24		61Sc19
294.9	0.96	0.57			0.35	A=156
276.9	2.53	0.93		2.5		cryst
255.6	1.32	0.65		2.0		I**
230.7	0.32	0.05		0.16		
199.4	10.28				7.7	5.0

* Listed intensities multiplied by 0.81 from those in (ND-2)
** Listed intensities multiplied by 0.18 from those in (ND-2)

9. ERBIUM RESULTS

9.1 Erbium Sample

Table 9.1 lists the sample characteristics and run information for erbium. The sample consists of 3.573 grams of erbium oxide powder placed in a poly vial of dimensions 1/2 inches diameter by 7/8 inches long. Erbium-167 contributes 90% of the captures in the sample, Erbium 9%, and the other isotopes less than 1%. The effective thermal neutron capture cross section for the sample is 170.77 barns, which was corrected using the Westcott factors to 268 barns. There was a relatively large flux depression for this sample of 0.604, and the average binding energy for the sample is 7638.0 keV. For the erbium sample it was necessary to use a 3 1/2 inch thick masonite neutron and gamma attenutator plug situated between the sample and Ge(Li) detector. This compares to using a 1 1/2 inch thick masonite plug for all the other results given in this work (see Sections 2.1 and 2.4.4). Appropriate corrections were made to the EFFCY array to account for the increased attenuation of the gamma beam caused by the larger thickness of masonite.

TABLE 9.1 ERBIUM SAMPLE DATA AND RUN INFORMATION

Sample: Er_2O_3 At. Wt.: 167.27

Wt: 3.13 gms Er Description: 3.573 gms. Oxide in Poly

Holder: Al Vial 1/2" diam. x 7/8.Vial Full.

Isotope:	Er^{166}	Er^{167}	Er^{168}	Er^{170}
Natural %:	33.41	22.94	27.07	14.88
Thermal Capture :	45b	650b	2.03b	96
Percent Captures in Natural Mixture:	9	90	0.3	0.8
Binding Energy of Product Nucleus: keV	6438	7770	5997	5676

Effective Capture Cross Section: $\sigma = 170.77b$

Westcott Correction: $\sigma_c = \sigma(g + rs) = \frac{170.77(1.325 + (0.017)(14.38))}{} = 268b$

Average Binding Energy for Sample: 7638.0 keV

Flux Depression Factor: $F_1 = .604$ $N_T\sigma_c = 3.02\ cm^2$ $\rho\bar{x} = 1.36\ gm/cm^2$

Data Collection Mode:	Compton Suppression	Pair Spectrometer
Run No:	11262	11261
Computer Job No:	J61132	J51203
Average Thermal Flux: ϕ ($n/cm^2 sec$)	$1.83 \times 10^{+8}$	$1.83 \times 10^{+8}$
Fraction of Sample Viewed by 1" Collimator: F_2	1.00	1.00
Collimator Used: Diam.	1/2"	1/2"
Duration of Run (Min):	130	1443
Dead Time Corrected Run Time: (Min) t	104	1443
SANGLE	1.58×10^{-5}	1.58×10^{-5}
$FLUXT = F_2 N_T \sigma_c \frac{F_1 \phi t}{100}$	$2.08 \times 10^{+10}$	$2.89 \times 10^{+11}$

9.2 Erbium Compton Suppression Results

Figure 9.1 shows the erbium Compton suppression spectrum, run 11262. Tables 9.2 and 9.3 gives the GAMANL parameters and GAMANL results for this data. A total of 50 peaks were analysed and printed out. Of these, 37 were capture peaks from the erbium sample, 11 were marginal peaks (tentatively assigned to erbium), and 2 were background peaks.

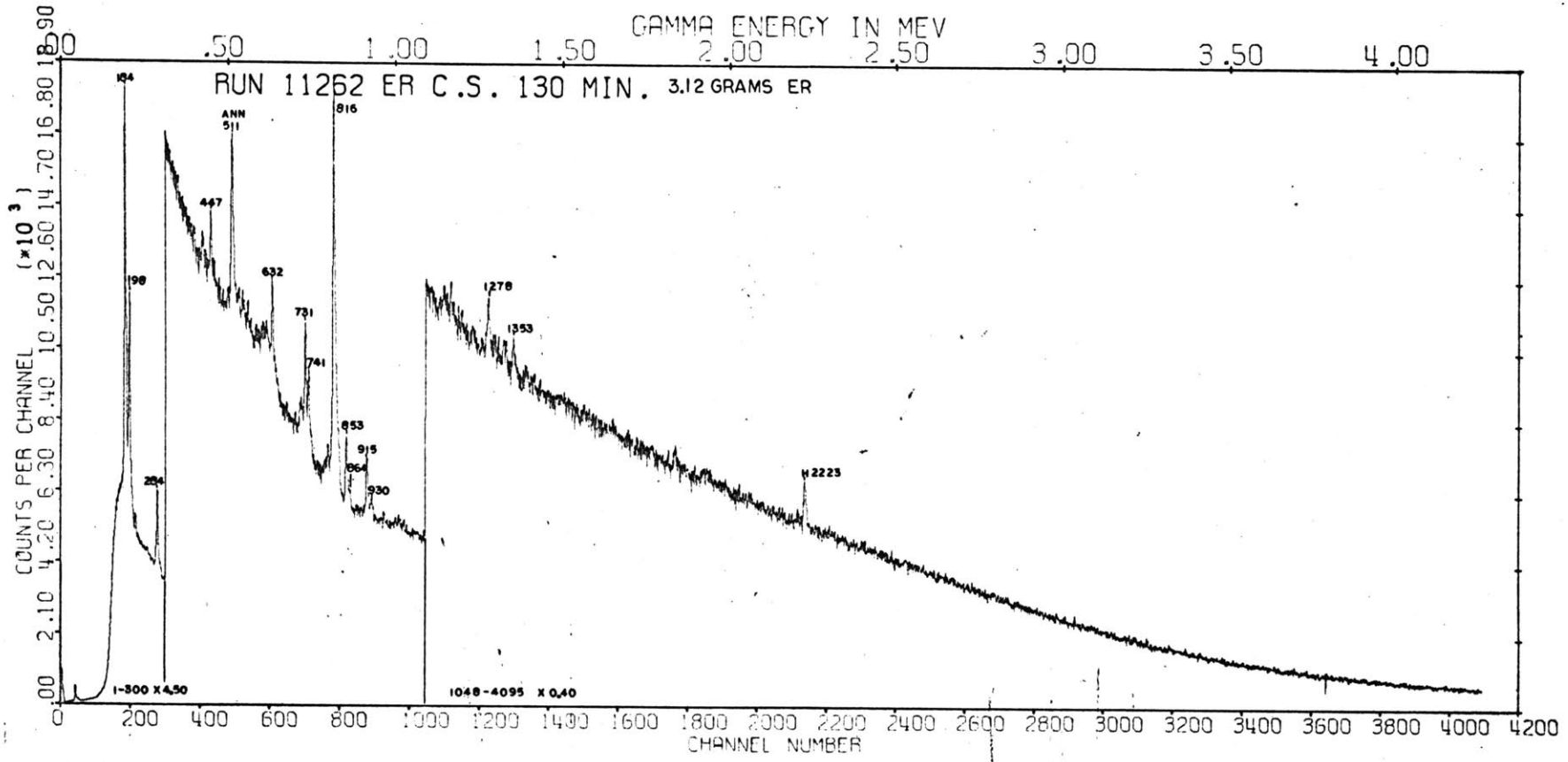

Figure 9.1 Erbium Compton Suppression Spectrum 11262

```
PARAMETERS AND INPUT DATA FOR RUN 11262  4095 CHANNELS

LINEAR RUN 11222 N2 =  10 N3 =  40 XN =  40.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  192
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   3.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   2.5
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS =  9.00 FWHM RANGE ERFW =  5.00
ENERGY PER CHANNEL NUMBER (KEV) = 1.039
CALIB1 E = 511.0 CNTR =  492 CORR = 490.6 FWHM =  6.79
CALIB2 E =2223.3 CNTR = 2138 CORR =2138.3 FWHM =  9.21
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.208E 11
FIRST EFFCY ENERGY(KEV)  200. DELTA ENERGY(KEV)  200.
 0.230E-01 0.143E-01 0.103E-01 0.845E-02 0.730E-02
 0.686E-02 0.583E-02 0.510E-02 0.460E-02 0.412E-02
 0.370E-02 0.326E-02 0.295E-02 0.265E-02 0.238E-02
 0.203E-02 0.184E-02 0.169E-02 0.142E-02 0.131E-02
 0.115E-02 0.101E-02 0.865E-03 0.770E-03 0.705E-03
 0.630E-03 0.557E-03 0.505E-03
NUMBER OF PEAKS ANALYSED = 50   J61132
```

Table 9.2 Erbium Compton Suppression Run 11262
GAMANL Parameters

PEAK ANALYSIS PAGE 1

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
1Er	198.0	197.1	22117.0	0.6979	113195.0	0.9	14.856	4.95	0.23E-01	18.	S *
					123367.5	0.9	16.191	5.08			
2Er	217.5	215.3	2144.6	0.0936	9785.6	5.4	1.346	4.73	0.22E-01	10.	S *
					12076.6	5.4	1.661	5.13			
3Er	254.3	249.5	569.5	0.0285	2567.3	17.5	0.386	4.62	0.20E-01	9.	S *
					3262.6	18.0	0.491	5.22			
4Er	269.8	264.0	512.9	0.0274	2106.0	18.9	0.329	4.35	0.19E-01	8.	S *
					2959.1	19.4	0.462	5.25			
5Er	284.1	277.4	10345.0	0.5798	72875.1	1.3	11.776	6.03	0.19E-01	23.	S *
					60071.2	1.4	9.707	5.29			
6Er	329.5	320.2	352.2	0.0226	1030.3	28.1	0.186	3.07	0.17E-01	6.	S *
					2086.0	25.6	0.376	5.39			
7Er	346.7	336.3	461.3	0.0305	1539.4	20.9	0.289	3.54	0.16E-01	7.	S *
					2751.6	19.4	0.516	5.43			
8Er	397.0	383.7	628.6	0.0468	2766.4	13.4	0.583	4.61	0.14E-01	9.	S *
					3825.3	13.6	0.806	5.54			
9Er	422.0	407.4	754.7	0.0578	4315.8	9.3	0.952	6.12	0.14E-01	10.	S *
					4637.0	11.3	1.023	5.59			
10x	431.5	416.3	331.1	0.0256	993.8	26.6	0.223	3.13	0.14E-01	6.	S *
					2041.7	24.9	0.458	5.61			
11Er	447.3	431.3	1447.6	0.1125	6688.2	6.4	1.542	4.72	0.13E-01	11.	S *
					8978.5	6.1	2.069	5.65			
12x	458.3	441.8	306.5	0.0243	984.0	29.8	0.231	3.35	0.13E-01	7.	S *
					1908.5	26.5	0.448	5.67			
13Er	472.4	455.3	356.5	0.0299	1917.1	18.2	0.461	6.00	0.13E-01	9.	S *
					2231.0	22.3	0.537	5.70			
14x	482.8	465.2	304.4	0.0260	944.1	26.7	0.231	3.25	0.12E-01	6.	S *
					1912.2	25.8	0.468	5.72			
15x	498.3	479.9	473.8	0.0400	1813.0	17.5	0.456	4.00	0.12E-01	8.	S *
					2992.1	16.9	0.752	5.75			

Table 9.3 Erbium Compton Suppression Run 11262 GAMANL Results

PEAK ANALYSIS PAGE 2

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
B	16An	511.0	492.1	5001.8	0.4183	36871.6	2.2	9.466	6.79	0.12E-01	24.	S *
						31727.4	2.1	8.146	5.77			
	17Er	532.2	512.3	434.3	0.0369	1511.4	18.8	0.402	3.65	0.11E-01	7.	S *
						2774.1	18.3	0.737	5.82			
	18Er	542.7	522.4	547.1	0.0481	4368.3	11.2	1.180	8.81	0.11E-01	14.	S *
						3507.1	14.4	0.948	5.84			
	19Er	558.1	537.0	641.4	0.0573	2392.5	12.9	0.662	3.84	0.11E-01	8.	S *
						4132.0	12.3	1.144	5.86			
	20Er	583.0	560.8	349.7	0.0326	1502.4	22.0	0.432	4.54	0.11E-01	9.	S *
						2270.3	21.6	0.652	5.91			
	21Er	615.5	591.9	296.0	0.0274	1436.9	25.1	0.430	5.06	0.10E-01	10.	S *
						1941.2	25.5	0.581	5.97			
	22Er	632.1	607.7	2179.5	0.2222	12203.1	6.5	3.718	6.01	0.10E-01	24.	D .017
						14378.7	3.9	4.381	6.01			
	23Er	639.9	615.2	323.5	0.0330	1821.1	6.5	0.559	6.01	0.99E-02	24.	D .017
						2134.4	22.3	0.656	6.01			
	24Er	676.1	649.9	294.4	0.0348	1509.0	19.5	0.481	5.84	0.95E-02	9.	S *
						1964.5	22.9	0.626	6.07			
	25x	699.6	672.4	311.7	0.0381	1110.3	21.4	0.362	3.75	0.93E-02	7.	S *
						2092.9	21.3	0.683	6.11			
	26Er	718.0	690.1	616.4	0.0740	5121.7	8.7	1.703	9.09	0.91E-02	15.	S *
						4159.5	11.2	1.383	6.14			
	27Er	730.8	702.4	2579.8	0.3012	12910.0	2.8	4.346	5.12	0.90E-02	11.	S *
						17465.2	3.3	5.879	6.16			
	28Er	741.3	712.6	1446.1	0.1740	6719.3	4.5	2.285	4.83	0.89E-02	9.	S *
						9816.4	5.2	3.338	6.18			
	29x	766.2	736.5	265.2	0.0384	793.8	27.4	0.276	3.20	0.87E-02	7.	S *
						1811.5	23.0	0.631	6.22			
	30Er	798.9	767.9	611.5	0.0862	2345.2	10.6	0.841	3.96	0.85E-02	8.	S *
						4209.2	10.6	1.509	6.27			
	31Er	816.0	784.5	11990.0	1.7730	112253.6	0.9	40.867	7.07	0.83E-02	40.	S *
						82863.4	1.3	30.167	6.29			

Table 9.3 (Continued) Er CS

PEAK ANALYSIS PAGE 3

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S / AREA-G COUNTS	ERR-S / ERR-G PCSD	INT-S / INT-G N/100C	FWHM-M / FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
32Er	853.4	820.4	1969.0	0.3344	13037.6	4.2	4.898	6.35	0.81E-02	23.	D .000
					13737.8	3.6	5.161	6.35			
33Er	864.3	830.9	471.5	0.0801	3152.7	4.2	1.195	6.35	0.80E-02	23.	D .000
					3289.4	12.4	1.247	6.35			
34x	898.1	863.3	242.6	0.0431	765.8	25.7	0.298	3.34	0.78E-02	7.	S *
					1706.2	22.8	0.664	6.40			
35Er	914.9	879.4	1510.1	0.2602	8981.4	4.2	3.537	5.66	0.77E-02	15.	S *
					10657.3	4.5	4.197	6.42			
36Er	930.5	894.4	372.9	0.0659	2526.5	12.1	1.006	7.27	0.76E-02	12.	S *
					2639.7	15.2	1.051	6.44			
37Er	965.6	928.1	307.3	0.0570	1242.8	18.9	0.506	4.21	0.74E-02	9.	S *
					2189.5	17.9	0.892	6.49			
38x	999.4	960.8	226.2	0.0427	823.8	25.7	0.342	3.77	0.73E-02	8.	S *
					1621.6	23.7	0.674	6.53			
39Er	1024.8	985.3	234.3	0.0452	858.5	24.4	0.358	3.84	0.73E-02	8.	S *
					1686.6	22.7	0.703	6.55			
40Er	1166.6	1120.9	338.0	0.0726	1330.2	15.0	0.578	4.12	0.70E-02	8.	S *
					2483.1	15.3	1.080	6.69			
41Er	1199.4	1152.5	225.2	0.0507	896.2	23.8	0.396	4.13	0.69E-02	9.	S *
					1660.7	22.0	0.734	6.71			
42Er	1278.2	1228.6	595.7	0.1420	5292.8	7.7	2.500	8.61	0.64E-02	20.	S *
					4430.2	8.9	2.093	6.77			
43Er	1308.7	1258.0	195.6	0.0479	898.9	22.7	0.435	4.83	0.63E-02	9.	S *
					1458.4	24.2	0.706	6.79			
44x	1324.0	1272.6	185.6	0.0450	925.8	24.1	0.454	5.33	0.62E-02	10.	S *
					1385.9	25.6	0.680	6.80			
45Er	1332.3	1280.6	202.3	0.0496	704.0	23.8	0.347	3.65	0.61E-02	7.	S *
					1511.8	23.5	0.746	6.80			
46Er	1352.9	1300.3	347.2	0.0882	2898.9	11.2	1.455	8.33	0.60E-02	16.	S *
					2598.9	14.0	1.304	6.81			
47x	1599.2	1537.4	163.1	0.0500	490.0	30.6	0.291	3.21	0.51E-02	7.	S *
					1234.0	26.1	0.734	6.89			

Table 9.3 (Continued) Er CS

PEAK ANALYSIS PAGE 4

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN	
48 Er	1835.9	1765.3	184.1	0.0647	1419.6	16.3	0.955	8.28	0.45E-02	13.	S *
					1387.2	22.1	0.933	6.86			
B 49 H	2223.3	2139.1	492.0	0.2288	4261.4	5.8	3.549	9.21	0.36E-02	16.	S *
					3571.7	10.8	2.975	6.61			
50 x	3792.5	3646.4	78.1	0.2169	227.6	22.5	0.484	3.08	0.14E-02	7.	S *
					253.3	162.6	0.538	2.95			

Table 9.3 (Continued) Er CS

9.3 Erbium Pair Spectrometer Results

Figure 9.2 shows the erbium pair spectrometer spectrum, run 11261. The spectrum shows strong well resolved peaks above 4.9 MeV, with a large unresolved continuum region extending from 1.5 MeV to 5.5 MeV.

Table 9.4 gives the GAMANL and GAMABC parameters for this data. Tables 9.5 and 9.6 present the GAMANL results and the GAMABC results. A total of 52 peaks were analysed and printed out. Of these, 43 are capture gamma peaks from erbium, 1 is a marginal peak (tentatively assigned to erbium), and 8 are background peaks. The GAMABC results of analysing the continuum show a large unresolved region from 1.7 MeV to 4.5 MeV, as indicated by the large intensity per energy bin width of 250 keV in Table 9.6. The threshold setting of the analyser introduces the negative intensity value for the first bin, and this should be disregarded.

The total observed percent fraction of the average binding energy of the erbium sample is 99.2%, with 16.0% being due to the resolved capture lines of erbium, and 83.2% being due to the unresolved capture gammas in the continuum. This 83.2% is broken into 77.9% due to the continuum above 2.0 MeV, and 5.3% due to the continuum below 2.0 MeV.

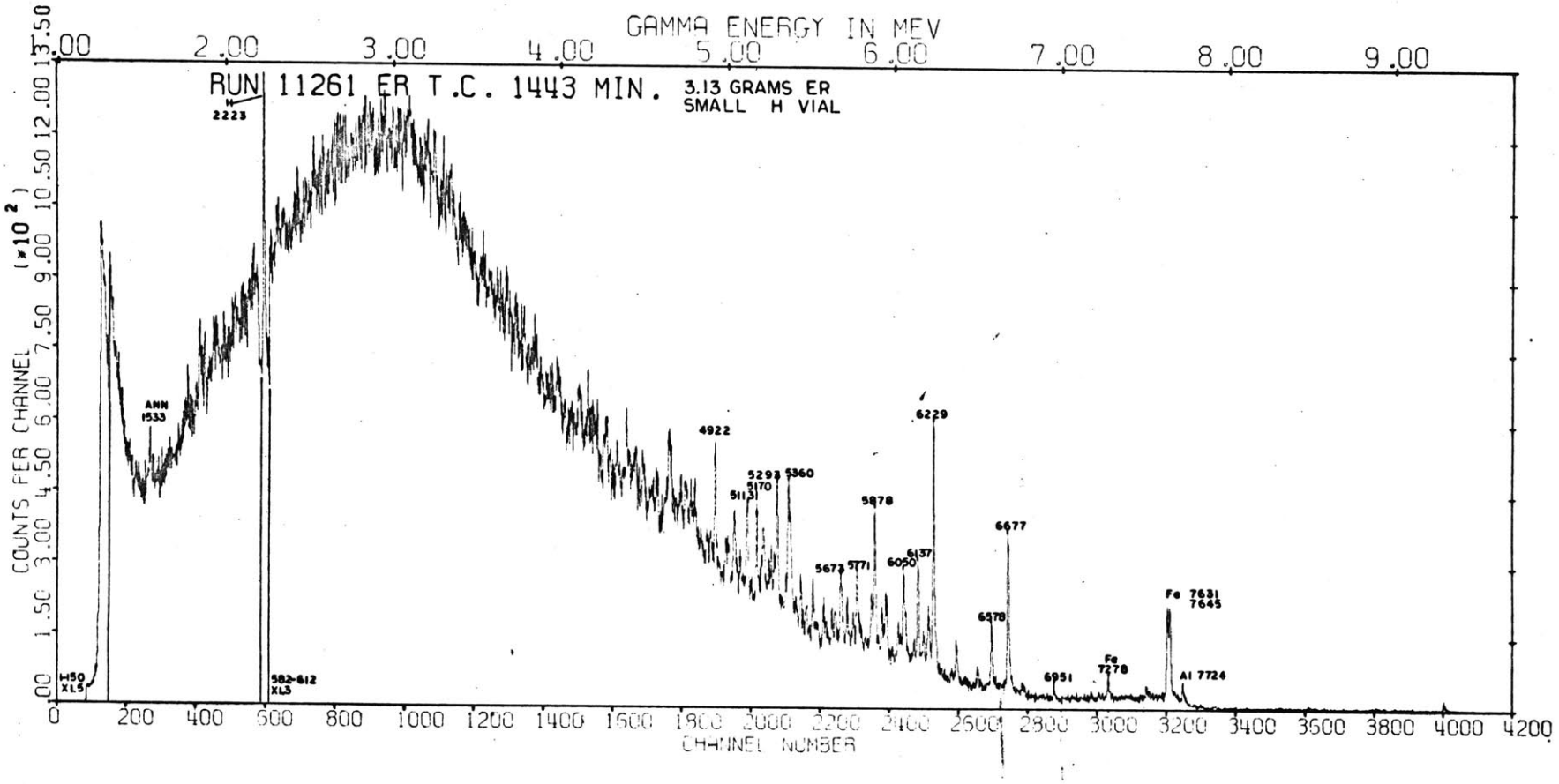

Figure 9.2 Erbium Pair Spectrometer Spectrum 11261

```
PARAMETERS AND INPUT DATA FOR RUN 11261  4095 CHANNELS

LINEAR RUN 11152 N2 =  15 N3 =  80 XN =  30.0
LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)  220
BACKGROUND CRITERION DCR * SQRT(BK) DCR =   3.0
NUMBER OF POINTS USED TO AVERAGE MINIMA =   7.0
PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK) BGER =   3.0
PERCENT RELATIVE STANDARD DEVIATION CRITERION ECR =  30.0
FIRST PEAK FWHM(KEV) FPS = 10.00 FWHM RANGE ERFW =  4.50
ENERGY PER CHANNEL NUMBER (KEV) = 2.076
CALIB1 E =2223.3 CNTR =  597 CORR = 596.5 FWHM =  9.69
CALIB2 E =7723.8 CNTR = 3248 CORR =3246.6 FWHM =  8.11
GEOMETRY FACTOR = 0.158E-04 NO OF CAPT/100 = 0.289E 12
FIRST EFFCY ENERGY(KEV) 1000. DELTA ENERGY(KEV)  500.
 0.600E-07 0.680E-04 0.185E-03 0.308E-03 0.450E-03
 0.580E-03 0.696E-03 0.740E-03 0.768E-03 0.770E-03
 0.765E-03 0.732E-03 0.690E-03 0.610E-03 0.542E-03
 0.470E-03 0.393E-03 0.316E-03 0.241E-03
NUMBER OF PEAKS ANALYSED = 52   J51203

GAMABC PEAK RESPONSE FUNCTION PARAMETERS
F2 = 0.00085 x AREA      F5 = 0.0015 x AREA
F3 = 0.00045 x AREA      F8 = 0.0045 x AREA
LOW CH = IMAX            MID CH = 900
W1 = 120 + 130 (E - 2200)/4610  for E ≤ 6810 keV
W1 = 250 + 125 (E - 6800)/ 450  for E > 6810 keV
W2 = 0.0004 x AREA + 2.0
W3 = 70
BAKFAC = 1.300   BIN WIDTH = 10 CHS   RED = 1.045
```

Table 9.4 Erbium Pair Spectrometer Run 11261
GAMANL and GAMABC Parameters

PEAK ANALYSIS PAGE 1

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S	ERR-S	INT-S	FWHM-M	EFF(E)	BASE	TYPE	
						AREA-G	ERR-G	INT-G	FWHM-C				
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/10CC	KEV	N/CTS	CHAN		
B	1An	1534.6	269.7	88.6	0.1802	312.3	23.1	0.898	7.13	0.76E-04	9.	S	*
						383.1	22.3	1.102	8.39				
	2Er	1834.8	410.9	122.7	0.1841	559.7	13.9	0.839	9.73	0.15E-03	8.	S	*
						534.5	18.2	0.801	8.45				
	3Er	1863.6	424.7	95.3	0.1410	298.4	23.3	0.427	6.58	0.15E-03	7.	S	*
						415.4	22.4	0.595	8.45				
	4Er	1979.4	480.2	92.1	0.1259	245.7	26.1	0.298	5.61	0.18E-03	6.	S	*
						402.9	23.6	0.488	8.48				
	5Er	2031.7	505.2	95.8	0.1259	251.8	26.0	0.286	5.51	0.19E-03	6.	S	*
						419.7	23.1	0.477	8.49				
B	6H	2223.3	596.9	790.0	0.8297	4046.9	4.4	3.719	9.69	0.24E-03	17.	S	*
						3479.7	5.7	3.197	8.54				
	7Er	2647.3	800.6	134.9	0.1242	401.1	19.6	0.249	6.22	0.35E-03	6.	S	*
						602.7	19.5	0.375	8.67				
	8x	3244.9	1088.2	113.6	0.1036	673.5	19.0	0.285	12.77	0.52E-03	9.	S	
						520.4	22.8	0.220	8.88				
	9Er	3674.2	1295.1	100.2	0.1243	674.5	20.8	0.234	14.93	0.63E-03	12.	S	
						468.1	22.5	0.163	9.06				
	10Er	4162.2	1529.9	135.1	0.2302	441.5	16.5	0.135	6.41	0.71E-03	8.	S	*
						647.7	15.6	0.199	9.29				
	11Er	4390.9	1640.4	112.1	0.2195	442.1	15.4	0.132	8.25	0.73E-03	8.	S	*
						544.1	17.3	0.162	9.42				
	12Er	4643.4	1762.2	98.5	0.2069	613.1	15.2	0.178	13.98	0.75E-03	10.	S	
						485.3	18.7	0.141	9.56				
	13Er	4742.9	1810.1	86.5	0.2170	638.8	16.7	0.184	17.51	0.76E-03	13.	S	
						428.9	19.6	0.124	9.61				
	14Er	4800.6	1837.9	77.1	0.1971	338.3	19.2	0.097	7.36	0.76E-03	9.	S	*
						383.5	21.5	0.110	9.65				
	15Er	4921.6	1896.3	249.6	0.7908	1244.4	6.3	0.355	9.71	0.77E-03	12.	S	*
						1251.2	8.4	0.357	9.72				

Table 9.5 Erbium Pair Spectrometer Run 11261 GAMANL Results

PEAK ANALYSIS PAGE 2

NO	ENERGY KEV	PK CNT CH NO	HEIGHT COUNTS	H TO B RATIO	AREA-S AREA-G COUNTS	ERR-S ERR-G PCSD	INT-S INT-G N/10CC	FWHM-M FWHM-C KEV	EFF(E) N/CTS	BASE CHAN	TYPE
16Er	5037.3	1952.2	126.0	0.4327	842.8	10.4	0.239	14.53	0.77E-03	12.	S
					636.3	13.2	0.181	9.79			
17Er	5071.2	1968.6	67.5	0.2544	311.3	18.8	0.088	9.35	0.77E-03	10.	S *
					341.7	20.9	0.097	9.81			
18Er	5113.2	1988.9	173.6	0.6663	1120.4	7.6	0.318	13.52	0.77E-03	12.	S
					880.8	10.2	0.250	9.84			
19Er	5170.1	2016.4	179.1	0.6856	765.8	7.5	0.217	8.92	0.77E-03	9.	S *
					911.9	10.0	0.259	9.88			
20Er	5212.4	2036.8	90.6	0.3096	514.5	13.9	0.146	11.82	0.77E-03	12.	S *
					462.8	17.0	0.131	9.90			
21Er	5257.9	2058.7	72.5	0.2684	242.1	20.4	0.069	6.61	0.77E-03	8.	S *
					371.6	19.8	0.105	9.93			
22Er	5292.8	2075.5	215.2	0.7953	1178.8	6.3	0.334	11.07	0.77E-03	12.	S *
					1105.1	8.8	0.313	9.96			
23Er	5360.0	2108.0	222.2	0.9218	1261.3	5.8	0.358	10.00	0.77E-03	20.	D .051
					1146.1	8.4	0.325	10.00			
24Er	5370.5	2113.1	167.0	0.6928	947.6	5.8	0.269	10.00	0.77E-03	20.	D .051
					861.4	10.2	0.244	10.00			
25Er	5433.6	2143.4	93.1	0.5182	499.7	11.5	0.142	10.50	0.77E-03	12.	S *
					482.4	14.5	0.137	10.05			
26Er	5469.8	2160.8	58.4	0.3498	365.2	14.9	0.104	13.78	0.77E-03	12.	S *
					303.1	20.3	0.086	10.07			
27Er	5506.4	2178.4	97.3	0.5846	527.5	10.6	0.150	9.87	0.77E-03	12.	S *
					506.9	13.8	0.144	10.10			
28Er	5570.5	2209.4	55.2	0.3412	236.8	16.6	0.067	9.18	0.77E-03	8.	S *
					288.9	21.0	0.082	10.14			
29Er	5620.2	2233.6	65.1	0.4364	269.5	17.7	0.076	8.03	0.77E-03	11.	S *
					341.7	18.0	0.097	10.18			
30Er	5638.3	2242.4	61.4	0.3954	314.1	14.6	0.089	11.88	0.77E-03	10.	S *
					322.8	19.1	0.091	10.19			
31Er	5673.1	2259.1	144.8	0.9695	1102.5	6.9	0.312	14.92	0.77E-03	18.	S *
					762.6	10.2	0.216	10.21			

Table 9.5 (Continued) Er PS

PEAK ANALYSIS PAGE 3

	NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
		KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/10CC	KEV	N/CTS	CHAN		
	32Er	5711.9	2277.7	80.9	0.5628	519.4	12.4	0.147	10.06	0.77E-03	16.	S	*
						427.4	15.2	0.121	10.24				
	33Er	5771.0	2306.3	145.0	0.9670	952.2	7.2	0.270	11.67	0.77E-03	16.	S	*
						769.0	10.2	0.218	10.28				
	34Er	5858.1	2348.4	106.6	0.7464	652.9	5.3	0.185	10.35	0.77E-03	26.	D	.000
						569.3	12.5	0.162	10.35				
	35Er	5878.1	2358.0	278.2	1.9475	1723.7	5.3	0.489	10.35	0.77E-03	26.	D	.000
						1485.3	6.8	0.422	10.35				
B	36Fe	5920.5	2378.4	66.5	0.4558	273.0	13.9	0.078	8.54	0.77E-03	8.	S	*
						356.6	17.6	0.101	10.39				
	37Er	5942.6	2389.1	62.4	0.3324	169.3	20.0	0.048	5.70	0.77E-03	6.	S	*
						334.9	19.9	0.095	10.41				
B	38Fe	6018.2	2425.6	51.0	0.3713	199.0	18.1	0.057	8.05	0.76E-03	8.	S	*
						275.1	21.2	0.079	10.46				
	39Er	6050.8	2441.4	147.0	1.0630	1047.5	7.6	0.300	16.32	0.76E-03	16.	S	
						795.1	10.0	0.228	10.49				
	40Er	6136.9	2482.9	202.8	1.7605	1150.5	4.9	0.332	11.42	0.76E-03	13.	S	*
						1104.0	8.0	0.318	10.55				
	41Er	6170.2	2499.0	45.2	0.3934	232.9	19.2	0.067	10.67	0.75E-03	12.	S	*
						246.5	22.2	0.071	10.58				
	42Er	6198.2	2512.5	88.1	0.7355	534.9	10.1	0.155	11.79	0.75E-03	14.	S	*
						481.6	13.7	0.140	10.60				
	43Er	6228.6	2527.2	505.9	4.3588	3049.6	2.9	0.886	10.55	0.75E-03	21.	S	*
						2771.7	4.8	0.806	10.62				
	44Er	6366.3	2593.7	68.2	0.9188	394.0	10.4	0.116	11.32	0.74E-03	13.	S	*
						377.7	14.9	0.111	10.73				
	45Er	6492.2	2654.4	41.5	0.7892	243.0	13.7	0.072	12.91	0.73E-03	13.	S	*
						232.0	19.5	0.069	10.83				
	46Er	6577.6	2695.6	120.2	1.8592	640.4	6.5	0.192	10.35	0.73E-03	13.	S	*
						675.6	10.3	0.203	10.90				
	47Er	6676.6	2743.2	314.9	4.8129	1865.6	3.2	0.564	11.43	0.72E-03	17.	S	*
						1783.7	6.2	0.540	10.98				

Table 9.5 (Continued) Er PS

PEAK ANALYSIS PAGE 4

NO	ENERGY	PK CNT	HEIGHT	H TO B	AREA-S AREA-G	ERR-S ERR-G	INT-S INT-G	FWHM-M FWHM-C	EFF(E)	BASE	TYPE	
	KEV	CH NO	COUNTS	RATIO	COUNTS	PCSD	N/100C	KEV	N/CTS	CHAN		
	48Er6951.4	2875.4	28.2	0.8755	81.3	22.6	0.026	6.00	0.70E-03	7.	S	
					162.9	23.2	0.051	11.22				
B	49Fe7276.2	3032.5	36.4	0.9600	132.5	20.0	0.045	6.80	0.64E-03	10.	S	
					216.3	20.8	0.073	11.51				
B	50Fe7629.5	3202.2	178.2	5.1721	1101.6	3.3	0.406	11.84	0.59E-03	28.	D	.015
					1088.5	12.9	0.401	11.84				
B	51Fe7644.3	3209.3	184.1	5.3421	1137.0	3.3	0.420	11.84	0.59E-03	28.	D	.015
					1124.3	12.8	0.415	11.84				
B	52A17723.8	3247.4	34.5	1.2505	154.4	14.0	0.058	8.11	0.58E-03	11.	S	*
					212.1	22.8	0.080	11.92				

Table 9.5 (Continued) Er PS

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 1

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
1	249	-6280.5	8636.5	45419.9	1500.0	-14.18	5.4
		46.7	-6327.2			0.0	
2	369	7019.7	9228.8	66596.1	1750.0	9.75	5.7
					1834.8	0.84	13.9
					1863.6	0.43	23.3
					1979.4	0.30	26.1
		7104.8	-85.1			1.56	
3	490	17476.9	10160.8	75396.6	2000.0	17.83	2.5
					2031.7	0.29	26.0
		17476.9	0.0			0.29	
4	610	29399.0	11148.5	81845.4	2250.0	23.72	1.6
		29399.0	0.0			0.0	
5	731	39709.0	11699.9	84506.5	2500.0	25.15	1.2
					2647.3	0.25	19.6
		39709.0	0.0			0.25	
6	851	47937.8	11620.0	84958.2	2750.0	25.20	1.0
		47937.8	0.0			0.0	
7	972	50778.1	10987.3	78443.0	3000.0	22.91	0.9
					3244.9	0.29	19.0
		50778.1	0.0			0.29	
8	1092	44596.4	10655.6	67588.4	3250.0	18.04	1.0
		44596.4	0.0			0.0	
9	1213	36600.9	9547.4	55804.4	3500.0	12.98	1.1
					3674.2	0.23	20.8
		36600.9	0.0			0.23	
10	1333	30047.3	8871.8	46056.9	3750.0	9.61	1.2
		30047.3	0.0			0.0	
11	1453	23990.5	8420.8	38743.7	4000.0	7.39	1.4
					4162.2	0.14	16.5
		23990.5	0.0			0.14	
12	1574	20926.1	7480.4	32209.1	4250.0	6.27	1.5
					4390.9	0.13	15.4
		20926.1	0.0			0.13	
13	1694	18531.1	6661.7	27621.3	4500.0	5.40	1.6
					4643.4	0.18	15.2
					4742.9	0.18	16.7
		18531.1	0.0			0.36	
14	1815	13998.8	5897.0	21585.4	4750.0	3.99	1.9
					4800.6	0.10	19.2
					4921.6	0.35	6.3
		13998.8	0.0			0.45	
15	1935	9185.4	5646.3	17839.8	5000.0	2.61	2.6
					5037.3	0.24	10.4
					5071.2	0.09	18.8
					5113.2	0.32	7.6

Table 9.6 Erbium Pair Spectrometer Run 11261
GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 2

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
					5170.1	0.22	7.5
					5212.4	0.15	13.9
		9185.4	0.0			1.01	
16	2056	7816.4	4624.2	13718.0	5250.0	2.23	2.7
					5257.9	0.07	20.4
					5292.8	0.33	6.3
					5360.0	0.36	5.8
					5370.5	0.27	5.8
					5433.6	0.14	11.5
					5469.8	0.10	14.9
		7816.4	0.0			1.27	
17	2176	4010.5	4017.9	10433.7	5500.0	1.14	4.5
					5506.4	0.15	10.6
					5570.5	0.07	16.6
					5620.2	0.08	17.7
					5638.3	0.09	14.6
					5673.1	0.31	6.9
					5711.9	0.15	12.4
		4010.5	0.0			0.84	
18	2297	4192.6	3715.7	9234.6	5750.0	1.19	4.1
					5771.0	0.27	7.2
					5858.1	0.19	5.3
					5878.1	0.49	5.3
					5942.6	0.05	20.0
		4193.7	-1.0			0.99	
19	2417	4143.9	2929.3	7183.2	6000.0	1.19	3.8
					6050.8	0.30	7.6
					6136.9	0.33	4.9
					6170.2	0.07	19.2
					6198.2	0.16	10.1
					6228.6	0.89	2.9
		4144.8	-0.8			1.74	
20	2538	1261.1	2569.2	3590.1	6250.0	0.37	9.3
					6366.3	0.12	10.4
					6492.2	0.07	13.7
		1368.8	-107.7			0.19	
21	2658	1309.2	2167.8	2630.3	6500.0	0.39	8.0
					6577.6	0.19	6.5
					6676.6	0.56	3.2
		1398.2	-89.0			0.76	
22	2778	515.5	1620.6	1060.2	6750.0	0.16	15.2
					6951.4	0.03	22.6
		652.3	-136.8			0.03	
23	2899	128.9	1496.7	919.7	7000.0	0.04	56.9
		338.2	-209.3			0.0	
24	3019	288.9	1386.9	1239.0	7250.0	0.10	26.5

Table 9.6 (Continued) Er PS GAMABC Results

ENERGY INTERVAL ANALYSIS BIN WIDTH = 250.0 KEV PAGE 3

BIN NO	L CH NO	BIN AR COUNTS	BKGND AR COUNTS	LEC AR COUNTS	ENERGY KEV	INT N/100C	ERR PCSD
		449.9	-161.0			0.0	
25	3140	461.1	1596.0	1198.4	7500.0	0.17	17.2
		580.4	-119.3			0.0	
26	3260	73.2	427.9	28.4	7750.0	0.03	47.2
		177.1	-103.9			0.0	
27	3381	22.8	183.4	-5.4	8000.0	0.01	98.9
		88.6	-65.7			0.0	
28	3501	26.1	242.8	-36.7	8250.0	0.01	93.5
		105.3	-79.2			0.0	
29	3622	-71.0	218.4	-168.6	8500.0	-0.03	24.9
		71.1	-142.1			0.0	
30	3742	-40.8	206.9	-139.3	8750.0	-0.02	46.1
		88.3	-129.1			0.0	
31	3862	12.1	101.2	-29.7	9000.0	0.01	141.7
		81.5	-69.4			0.0	
32	3983	142.6	20.2	7.2	9250.0	0.10	-10.9
		164.7	-22.2			0.0	

FRACTION OF GAMMA RAYS OBSERVED
AVERAGE BINDING ENERGY (KEV) = 7770.00
UNRES = 80.5 -3.0 = 77.5%RES = 6.5%TOTAL = 84.0%
CS UNRES (EST) = 5.7% CS RES = 9.5% TOTAL ALL = 99.2%

NOTE: For shielding calculations, see Table 10.1 which normalizes the above results so that 100% of the average binding energy of the sample is observed.

Table 9.6 (Continued) Er PS GAMABC Results

9.4 Erbium Comparison of Results

Table 9.7 shows a comparison of the results of this work with the published data for the intensities of the strong capture lines of erbium. The energies of the gamma lines as found in this work are also given. The main source of the published listing of these intensities is Nuclear Data (ND-3). The results in general agree quite well with the published data, though the intensities of some of the stronger low energy lines appear to be somewhat higher than the other listed intensity values.

Table 9.7 Erbium Comparison of Results

Strong peaks only, I > 0.03 for E > 5.5 MeV, I > 0.20 for E ≤ 5.5 MeV, I given in number of gamma rays of energy E emitted per 100 captures in the Erbium sample.

Present Work		Nuclear Data Tables (ND-3)		
		MIT-NE-85	Groshev	
		R-1	65Gr32	
Energy keV	semi I	semi I	semi I	
				Priestwich
6951.4	0.03		0.03	67Pr11
6676.6	0.56	0.43	0.46	A = 167
6577.6	0.19	0.19	0.16	semi
6492.2	0.07	0.04	0.05	I**
6366.3	0.12	0.12	0.11	
6228.6	0.89	0.74	0.56	0.90
6198.2	0.16	0.16	0.15	
6170.2	0.07	0.08	0.08	0.20
6136.9	0.33	0.26	0.30	
6050.8	0.30	0.12	0.30	
5942.6	0.05		0.17	
5878.1	0.49	0.26	0.36	
5858.1	0.18	0.04	0.16	
5771.0	0.27	0.23	0.22	
5711.9	0.15	0.11	0.12	
5673.1	0.31	0.18	0.18	
5638.3	0.09	0.08		
5620.2	0.08	0.08		
5570.5	0.07	0.04	0.12	
5506.4	0.15	0.09	0.14	
5370.5	0.27	0.06	0.51	
5360.0	0.36	0.20		
5292.8	0.33	0.33	0.30	
5170.1	0.22	0.26	0.21	
5113.2	0.32	0.28	0.34	
5037.3	0.24	0.33	0.26	
4921.6	0.36	0.41		
3674.2	0.23	0.33		Koch
2647.3	0.25			66Ko03
2031.7	0.29			A = 168
1979.4	0.30			cryst
1863.6	0.43			I*
1835.9	0.96	0.93		
1352.9	1.46	1.11	2.96	1.26
1332.3	0.35			0.45
1308.7	0.43	1.29	1.29	0.34
1278.2	2.50	2.33	4.07	2.07
1199.4	0.40		0.76	0.37

* Listed intensities multiplied by 0.90 from those in (ND-3)
** Listed intensities multiplied by 0.09 from those in (ND-3)

Table 9.7 (Continued) Erbium Comparison of Results

Present Work		MIT-NE-85 R-1	Groshev 65Gr32	Koch 66Ko03
Energy keV	semi I	semi I	s Cp I	cryst A = 168 I*
1166.6	0.58		1.51	1.17
1024.8	0.36	0.27	1.61	0.72
965.6	0.51	0.46	1.14	0.72
930.5	1.01	1.04	1.70	0.90
914.9	3.54	3.62	5.25	5.40
864.3	1.19	0.47	2.37	0.81
853.4	4.90	3.35	4.66	5.58
816.0	40.87	26.25	36.0	32.4
798.9	0.84	1.05		1.90
741.3	2.29	4.09	5.26	5.94
730.8	4.35	6.04	11.1	11.3
718.0	1.70	1.24	3.65	1.98
676.1	0.48			0.42
639.9	0.56			0.73
632.1	3.72	3.01	5.45	5.94
615.5	0.43	0.48		0.07
583.0	0.43	0.14		0.17
558.1	0.66	1.10		1.64
542.7	1.18	1.03		1.47
532.2	0.40	0.15		0.29
472.4	0.46			0.20
447.3	1.54	1.55		2.07
422.0	0.95	0.78		1.08
397.0	0.58	0.15		0.57
346.7	0.29		Giannini	0.04
284.1	11.78	9.53	63Gi06	8.19
269.8	0.33	0.20	scin	0.20
254.3	0.39	0.38	I	0.42
217.5	1.35	0.90		1.55
198.0	14.86		23	19.8
184.3			61	29.7

* Listed intensities multiplied by 0.90 from those in (ND-3)

10. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE WORK

10.1 Summary

Table 10.1 lists the intensities per energy bin width of 250 keV for the five rare earth samples studied in this work. The listed intensities are normalized so that the observed percent average binding energy is 100% ± 1.0%. The data used to obtain the values of table 10.1 are those given in the previous five chapters. The normalization process used to obtain the results of table 10.1 consisted of taking the results of the GAMABC analysis for the particular sample studied and dividing the total gamma intensity per energy bin by the total fraction of observed binding energy as given in the GAMABC results table. For intensities below gamma energy of 1.5 MeV, the values of table 10.1 include the estimated intensity due to the unresolved capture gamma lines.

Thus for all of the energy bins shown, the intensities include both the intensities which lie within the energy bin from the resolved capture gamma peaks and from the unresolved capture lines as determined from the spectrum continuum portion.

The results for Gd and Er include the resolved gamma peak intensity values for lines at 182 keV and 184 keV respectively. These two lines were not listed in the

Table 10.1

Normalized Thermal Neutron Capture Intensities for Nd, Sm, Eu, Gd, and Er.

Energy Bin keV	Intensity in Number of Photons/100 Captures				
	Nd	Sm	Eu	Gd	Er
7750-8000	0.00	0.03	0.00	0.00	0.00
7500-7750	0.44	0.51	0.44	0.41	0.17
7250-7500	0.20	0.42	0.19	0.31	0.10
7000-7250	0.73	1.37	0.09	0.09	0.04
6750-7000	0.21	0.34	0.14	0.51	0.19
6500-6750	9.09	0.53	0.00	2.99	1.15
6250-6500	5.77	0.52	0.28	1.13	0.56
6000-6250	1.73	0.45	0.98	1.08	2.93
5750-6000	1.04	1.40	1.43	2.60	2.20
5550-5750	3.70	2.05	1.91	3.38	1.98
5250-5500	4.27	1.86	2.36	2.63	3.50
5000-5250	1.58	2.18	2.29	3.69	3.62
4750-5000	7.16	3.51	3.07	4.89	4.44
4500-4750	7.01	4.16	3.75	4.70	5.76
4250-4500	7.19	5.10	4.74	6.10	6.40
4000-4250	6.74	6.04	6.27	6.97	7.53
3750-4000	6.40	7.23	7.78	8.73	9.61
3500-3750	6.13	9.87	10.17	10.77	13.21
3250-3500	9.68	12.89	12.98	13.74	18.04
3000-3250	10.45	15.78	15.84	18.99	23.20
2750-3000	12.97	21.10	19.29	23.51	25.20
2500-2750	15.70	25.49	23.82	26.45	25.40
2250-2500	18.75	30.40	27.98	26.92	23.72
2000-2250	17.90	29.27	26.28	23.65	18.12
1750-2000	12.56	23.08	19.15	19.73	14.81
1500-1750	9.53	18.72	14.25	14.73	7.30
1250-1500	14.43	16.01	11.12	15.81	8.60
1000-1250	6.58	19.50	8.34	33.15	1.76
750-1000	29.12	13.21	5.45	40.70	53.77
500- 750	119.21	53.06	3.67	6.86	16.56
250- 500	14.36	169.21	4.00	4.83	17.65
0- 250	1.57	1.02	7.31	50.50(a)	77.21(b)
%$\overline{BE}$	99.7	100.0	99.2	100.7	100.7
$\overline{BE}$(keV)	7480.0	7981.9	6294.8	8038.1	7638.0

(a) Includes 182 keVline, I = 44.0
(b) Includes 184 keVline, I = 61.0

results of Chapters 8 and 9 since their energies were below 200 keV, the gamma energy cutoff for the data.

Table 10.1 also shows the actual value of the observed normalized fraction of binding energy as calculated by using the intensities listed in the table. The observed normalized fractions are not exactly equal to 100% due to the fact that in the previous chapters, this fraction was calculated by using the resolved peak intensities weighted by the peak energy divided by the binding energy, whereas for the calculation in table 10.1, these peak intensities are combined with the bin intensities from unresolved gammas and the total is weighted by the average energy of the bin divided by the binding energy. The calculated fractions obtained by using this method give results that are within $\pm$ 1.0% of 100% for the cases shown.

Table 10.1 thus presents a consistent set of capture gamma yields versus energy for the samples studied.

10.2 Conclusions

This work has shown that data from a Ge(Li) pair spectrometer can be analysed to obtain information on the energy and capture gamma yields from both the unresolved gamma continuum in a spectrum, as well as from the resolved capture peaks in a spectrum. For the samples studied, it is not sufficient to study only the resolved

capture lines, as most of the emitted energy is located in the unresolved continuum portions of the spectra.

A method of analysis of the unresolved continuum portions of a pair spectrometer spectrum has been developed which uses the Ge(Li) pair spectrometer system response to monoenergetic gamma rays. Results of this method of analysis have been presented for Nd, Sm, Eu, Gd, and Er. These results have indicated that this method of analysis is of sufficent accuracy to account for the emitted energy due to the intensity of the unresolved capture lines in the continuum.

10.3 Recommendations for Future Work

Since this method of analysis has worked successfully on the samples studied, it is recommended that the method be applied to other pair spectrometer capture gamma data. Specifically the analysis should be applied to the data used in obtaining report MITNE-85 (R-1). Particular emphasis should be placed upon studying the cases in which only a small fraction of the binding energy is observed. It is also recommended that this method be used to analyse any new capture gamma data taken which show evidence of having a significant continuum portion in the data spectrum due to unresolved gammas.

The following additional recommendations are made.

(1) The development and use of a Ge(Li) crystal with

a large active volume, small dead region, fast timing, and low capacitance is suggested. Such crystals are now available, and the use of a large planar detector is recommended with modifications made to reduce the size of the detector mounting assembly in order to improve the performance of the Compton suppression operation. Coupled with the use of a new detector should be a thorough study of the available electronic components for use in operating the spectrometer without resolution degradation at counting rates greater than 10,000 counts per second.

(2) If the detector time response is improved, further investigation of the optimum timing and window width settings for the pair spectrometer should be performed.

(3) The continuum analysis has shown that it is necessary to determine the system peak response function quite accurately and to account for its variation with gamma peak energy. Therefore, it is recommended that:

(A) A detailed study be carried out on the Ge(Li) detector response for the gamma peak energy range 1.5 MeV to 10.0 MeV with emphasis placed upon studying the low energy sontinuum observed,

(B) An investigation be performed upon the feasibility of constructing a theoretical model to predict the response function.

(4) The following experimental uses of the Ge(Li) capture gamma spectrometer are recommended:

(A) Investigation of separated isotope samples for many of the elements of interest in shielding and nuclear engineering work;

(B) Further study of high Z materials, $Z \geq 83$, in particular, study of uranium and plutonium isotopes;

(C) Re-investigation of the capture gamma spectra of Yttrium-89; the product nucleus, Yttrium-90, has one predominent capture line at 6080 keV which accounts for most of the emitted energy of Yt; this line is of interest from both a nuclear physics viewpoint, as well as by indicating the possibility of using Yt as a high energy monoenergetic capture gamma source;

(D) Use as a high resolution spectrometer to investigate the level structure, and spins and parities of the lines, by studying the amount of Doppler broadening seen in the measured FWHM of the capture gamma lines, see Wetzel (W-2); in this regard, the use of Fourier smoothing to obtain improved peak resolution (H-1) should be considered.

Appendix A Error Estimate in Summation Area Calculation

Using the notation of section 3.3.2, the equation for the area under a gamma peak as calculated by the summation method (as given by equation 3-4) is given as:

$$AREAS = \sum_{I=LO+1}^{I=LUP-1} DATA(I) + (1/2)\,(DATA(LO) + DATA(LUP)) - (N-1)\,\bar{B} \quad , \quad (A\text{-}1)$$

where AREAS is the area under a peak in counts, DATA(I) is the counts/channel at the I-th channel in the spectrum, LO is the channel number of the minimum point on the low energy side of the peak, LUP is the channel number of the minimum point on the high energy side of the peak, $N - 1 = LUP - LO - 1$ is the width of the peak at its base in channel numbers, $\bar{B}$ is the average background under the peak in counts/channel, and the summation for I is taken over all of the channels between channel numbers LO and LUP.

The average background under the peak is given by:

$$\bar{B} = (1/2)\left((1/M)\sum_{I} DATA(I) + (1/L)\sum_{I} DATA(I) \right), \quad (A\text{-}2)$$

where M is the number of channels used to average the high energy side minimum, L is the number of channels used to average the low energy side minimum, and the summations are taken over M and L channels respectively near channel numbers LUP and LO.

Error analysis upon equation A-1 gives:

$$\sigma^2(\text{AREAS}) = \sum_{I=LO+1}^{I=LUP-1} \sigma^2(\text{DATA}(I)) + (N-1)^2\,\sigma^2(\bar{B}) + (1/4)\,(\sigma^2(\text{DATA}(LO)) + \sigma^2(\text{DATA}(LUP)) \quad (A-3)$$

where $\sigma^2(X)$ represents the square of the standard deviation of the quantity X.

Equation A-3 expresses the error proagation of each term in equation A-1 as the sum of the squares of the standard deviation in each term. Equation A-3 neglects the uncertainty in the (N - 1) termswhich is the width in channel numbers of the peak at its base.

For counting statistics one has:

$$\sigma^2(\text{DATA}(I)) = \text{DATA}(I) \quad \text{for each channel in the spectrum,} \quad (A-4)$$

and

$$\sigma^2(\bar{B}) = (1/4)\left((1/M^2)\sum_I \text{DATA}(I) + (1/L^2)\sum_I \text{DATA}(I)\right). \quad (A-5)$$

Equations A-4 and A-2 were used to obtain equation A-5.

If one assumes $L = M$ for the number of points used to average the minimum points on each side of the peak, equation A-5 becomes upon using equation A-2:

$$\sigma^2(\bar{B}) = \frac{1}{2M}\,\bar{B} \quad . \quad (A-6)$$

Substituting equation A-6 and A-4 into equation A-3 gives:

$$\sigma^2(\text{AREAS}) = \sum_{I=LO+1}^{I=LUP-1} DATA(I) + (1/4)\,(DATA(LO) + DATA(LUP)) + (N-1)^2 \frac{\bar{B}}{2M} . \qquad (A\text{-}7)$$

The DATA terms of equation A-7 equal the peak area plus the background area under the peak. Writing this background area as $AREAB = (N-1)\,\bar{B}$, and substituting this value into equation A-7 gives:

$$\sigma^2(\text{AREAS}) = \text{AREAS} + \text{AREAB} - \frac{\bar{B}}{2} + (N-1)^2 \frac{\bar{B}}{2M}, \qquad (A\text{-}8)$$

or

$$\sigma^2(\text{AREAS}) = \text{AREAS} + \text{AREAB}\left(1 + \frac{(N-1)}{2M} - \frac{1}{2(N-1)}\right) . \qquad (A\text{-}9)$$

The percent relative standard deviation is then obtained from equation A-9 as:

$$\frac{100\,\sigma(\text{AREAS})}{\text{AREAS}} = \frac{100}{\sqrt{\text{AREAS}}}\sqrt{1 + \frac{\text{AREAB}}{\text{AREAS}}\left(1 + \frac{(N-1)}{2M} - \frac{1}{2(N-1)}\right)} . \qquad (A\text{-}10)$$

Equation A-10 expresses the relative standard deviation of the area as calculated by the summation method, in terms (1) of the peak area AREAS, (2) of the background area under the peak, AREAB, (3) of the base of the peak in channels (N - 1), and (4) of the average number of channel numbers, M, used in averaging the minimum points on each side of the peak.

The values of the percent relative standard deviation of the AREAS value for the peak area are printed out by the GAMANL code and are presented in the GAMANL results given for the data.

Appendix B Error Estimate in Gaussian Method Area Calculation

Equation 3-7, which gives the area under a peak as calculated by using the Gaussian method, is rewritten as:

$$\text{AREAG} = 1.0645 \times F \times \text{PKHT} \times \text{FWHM} \quad , \qquad \text{(B-1)}$$

where AREAG is the area under a peak in counts, F is the correction factor to correct for the non-Gaussian shapes of the peaks, PKHT is the peak height in counts/channel of the peak, and FWHM is the full width at half maximum in channel numbers of the peak.

Error analysis on equation B-1 gives:

$$\frac{\sigma^2(\text{AREAG})}{\text{AREAG}^2} = \frac{\sigma^2(F)}{F^2} + \frac{\sigma^2(\text{PKHT})}{\text{PKHT}^2} + \frac{\sigma^2(\text{FWHM})}{\text{FWHM}^2} \quad . \qquad \text{(B-2)}$$

The $\sigma^2(X)/X^2$ terms of equation B-2 are the squared relative standard deviation terms of the parameter X.

Equation B-2 is rewritten as a percent relative standard deviation for AREAG, after assuming that the uncertainty in F is negigible compared with the other two terms of equation B-2, as:

$$\frac{100\,\sigma(\text{AREAG})}{\text{AREAG}} = 100 \times \sqrt{\frac{\sigma^2(\text{PKHT})}{\text{PKHT}^2} + \frac{\sigma^2(\text{FWHM})}{\text{FWHM}^2}} \quad . \qquad \text{(B-3)}$$

The error in the peak height must include both statistical effects of the recorded data, as well as the un-

certainty in the method of determining the peak height. For this work, the peak height uncertainty is approximated as:

$$\sigma^2(\text{PKHT}) = \sigma^2(\text{DATA(MAX)}) + \sigma^2(\bar{B}) \quad , \qquad \text{(B-4)}$$

where $\sigma^2(\text{DATA(MAX)})$ is the square of the standard deviation of the recorded data at the peak maximum channel, MAX, $\sigma^2(\bar{B})$ is the square of the standard deviation of the average background under the peak.

The standard deviation of the recorded data at channel number MAX is assumed to follow counting statistics so that:

$$\sigma^2(\text{DATA(MAX)}) = \text{DATA(MAX)} \simeq \text{PKHT} + \bar{B} \quad . \qquad \text{(B-5)}$$

The standard deviation for the average background under the peak is given by equation A-6 of Appendix A as:

$$\sigma^2(\bar{B}) = \frac{1}{2M}\,\bar{B} \quad . \qquad \text{(B-6)}$$

Substituting equations B-5 and B-6 into B-4 gives:

$$\sigma^2(\text{PKHT}) = \text{PKHT} + \bar{B} + \frac{1}{2M}\,\bar{B} \quad . \qquad \text{(B-7)}$$

Substituting equation B-7 into B-3 gives:

$$\frac{100\ \sigma(\text{AREAG})}{\text{AREAG}} = 100\sqrt{\frac{1}{\text{PKHT}} + \left(1 + \frac{1}{2M}\right)\frac{\bar{B}}{\text{PKHT}^2} + \frac{\sigma^2(\text{FWHM})}{\text{FWHM}^2}} \qquad \text{(B-8)}$$

Equation B-8 expresses the percent relative standard deviation in the area AREAG, as calculated by the Gaussian method, in terms of: (1) the peak height, PKHT, in counts/channel, (2) the average background under the peak, $\bar{B}$, in counts/channel, (3) the number of points used to average the minimum points of the peak, M, and (4) the square of the relative standard deviation of the full width at half maximum of the peak, $\sigma^2(\text{FWHM}) / \text{FWHM}^2$.

In order to obtain a low value for the error in the FWHM, a least squares fit of the measured FWHM values (in keV) of the strong singlet peaks is made to a second order equation in peak energy (MeV, full energy value of the peak). After the second order equation is determined, the FWHM and the FWHM error of any peak can be found from the peak energy. The method uses essentially data from all of the gamma peaks to obtain the FWHM of a particular peak. Consequently, the error of the FWHM so obtained is reduced from the error obtained by a straight foreward measurement and error analysis of the FWHM for a single peak.

The GAMANL code performs the least squares fit on the measured FWHM as described above. From this fit, an appropriate equation for the error in the calculated FWHM is obtained. This error in the FWHM is used in equation B-8 along with the other terms to obtain the error estimate for the Gaussian area calculation. This error estimate is printed out in the GAMANL results for each peak studied.

Appendix C Discussion of Area Calculation Methods

It is desirable to know which method of area calculation is to be preferred in the analysis of the spectral data. An indication of the preferred method to use is obtained by the calculated estimate of the error in the area, with the method which gives the lower estimate being the one chosen. However, depending upon the peak parameters and the background levels of the spectral data being studied, it is possible for either area calculation method to give the more accurate results. Thus for the data presented in this work, both methods of area calculation are used, and the results presented. These results provide a cross check on both the area calculation method being used and on the peak being studied.

Hamawi (H-2) has discussed in detail which of the two area calculation methods is more reliable. Generally it is found that for the cases when a peak multiplet is being analysed, the Gaussian method gives a more accurate estimate of the area than the estimate obtained using the summation method. However, in cases where the error in the calculated peak full width at half maximum is too large, the summation method gives a better estimate of the peak area and its uncertainty.

As shown in equation B-8 of Appendix B, the error in the area, as calculated by the Gaussian method, depends upon the relative error in the peak FWHM. The least

squares fitting procedure for the FWHM works well in most of the cases studied. However, Wetzel (W-2) has shown that in the case of any gamma transition that follows an El transition in a gamma cascade, the Doppler broadening of the measured gamma peak may not be negligible. As a consequence, the measured FWHM and its error will depend upon the type of transition and its place in the level structure of the isotope being studied.

The amount of broadening depends directly upon the product of the energies of the cascade gammas involved, and inversely upon the mass of the excited nucleus. The effect is most pronounced for the cases when low Z materials are studied. The amount of broadening can vary the FWHM by $\sim$ 1.0 keV for two 5.0 MeV lines in cascade in boron A = 10, to $\sim$ 0.19 keV for two 5.0 MeV lines in cascade in neodymium A = 143. Since typical values of the FWHM are 5.0 keV to 10.0 keV, this broadening represents a variation of 10% to 20% for boron, and 2% to 4% for neodymium. Thus for neodymium and and heavier elements, it is felt that the Doppler broadening of the cascade gamma lines is not a severe detriment to the Gaussian method of peak area analysis.

For lower Z materials, such as the boron example cited, the spectral data should be studied in more detail to determine if the Doppler broadening of some of the resolved peaks will perturb the FWHM fit being performed.

For the beryllium and iron samples studied in Chapter 4, no problems were encountered, in obtaining a good least squares fit of the FWHM to peak energy, from Doppler broadening of the resolved lines. The GAMANL results for these cases show good agreement between the two methods of area calculation.

It is noted that in the error analysis equations of Appendices A and B, no allowance has been made for the reduction in the statistical error in counts per channel number of the spectral data due to the Fourier analysis and smoothing of the recorded data. This enables one to assume that the recorded data in each channel is un-correlated with data in neighboring channels, and simplifies the error equations so obtained.

The error equations of Appendices A and B are felt to be of sufficient accuracy to permit their use in predicting the uncertainty in the peak intensity values to a desired degree of accuracy.

Appendix D Error Estimate in Intensity Calculation

The peak intensity in number of photons of energy E emitted per 100 captures in the sample is given by equation 3-8 and rewritten here as:

$$INT = \frac{AREA}{Eff(E)\ Tsa(E)\ Tma(E)\ g\ \left(\frac{F_2 N \hat{\sigma} F_1 \phi t}{100} \right)} \quad \text{(D-1)}$$

The terms in equation D-1 are as defined in section 3.4, Chapter 3. Error analysis upon equation D-1 gives:

$$\frac{\sigma^2(INT)}{INT^2} = \frac{\sigma^2(AREA)}{AREA^2} + \frac{\sigma^2(Eff(E))}{Eff(E)^2} + \frac{\sigma^2(Tsa(E))}{Tsa(E)^2}$$
$$+ \frac{\sigma^2(Tma(E))}{Tma(E)^2} + \frac{\sigma^2(g)}{g^2} + \frac{\sigma^2(F_2N)}{F_2N^2}$$
$$+ \frac{\sigma^2(\hat{\sigma})}{\hat{\sigma}^2} + \frac{\sigma^2(F_1)}{F_1^2} + \frac{\sigma^2(\phi)}{\phi^2} + \frac{\sigma^2(t)}{t^2} . \quad \text{(D-2)}$$

The $\sigma^2(X) / X^2$ terms in equation D-2 represent the square of the standard deviation of the term X divided by X^2.

The table D-1 gives the values used for the various fractional standard deviations needed to evaluate equation D-2. Inserting the values shown in table D-1 into equation D-2 gives a range of relative uncertainties in the intensity value of ± 12% to ± 24%, with a typical

Table D-1

Uncertainties in the Terms used to Evaluate Capture Gamma Intensities

Term	Function	Relative Standard Deviation
AREA	Peak area in counts.	5%-15%
Eff(E)	Intrinsic efficiency of Ge(Li) detecting system in number of photons/ counts.	5%-10%
$T_{SA}(E)$	Transmission factor to account for sample self-absorption.	2%
$T_{MA}(E)$	Transmission factor to account for masonite gamma attenuation.	2%
g	Geometry solid angle factor.	5%
F_2N	Fraction of sample seen by detector with 1 inch collimator	5%
$\hat{\sigma}$	Effective capture cross section of sample.	5%
F_1	Flux depression correction factor.	3%
Φ	Thermal neutron flux at surface of sample.	5%-10%
t	Duration of the data run.	1%

value being $\sim \pm 15\%$ for the relative standard deviation (one sigma value) for the measured intensity.

The main terms contributing to the uncertainty in the intensity value, as shown in table D-1, are: (1) the measured intrinsic efficiency of the detector, (2) the thermal neutron flux at the sample surface, and (3) the peak area in the cases where the peak area is small and has high statistical uncertainty.

Appendix E Error Estimate in Observed Fraction of Binding Energy Calculation

The observed fraction of the average sample binding energy is given by equation 3-15, which is rewritten as:

$$F = \sum_{I} \frac{I(I)\ E(I)}{\overline{BE}} \quad , \qquad \text{(E-1)}$$

with the terms as defined in section 3.5. The summation, I, is taken over all of the resolved capture peaks as found in the pair spectrometer and Compton suppression results.

Error analysis upon equation E-1 gives:

$$\sigma^2(F) = \sum_{I} \sigma^2\left(\frac{I(I)\ E(I)}{\overline{BE}}\right) \quad , \qquad \text{(E-2)}$$

where the $\sigma^2(X)$ terms represent the squared standard deviation of the term X within the brackets.

If Y(I) represents the I-th term of equation E-1, then the relative standard deviation of Y(I) is given by:

$$\frac{\sigma^2(Y(I))}{(Y(I))^2} = \frac{\sigma^2(I(I))}{(I(I))^2} + \frac{\sigma^2(E(I))}{(E(I))^2} + \frac{\sigma^2(\overline{BE})}{(\overline{BE})^2} \quad . \qquad \text{(E-3)}$$

The intensity uncertainty term in equation E-3 is approximated as $\sigma(I(I)) / I(I) \leq \pm 15\%$ from the results of Appendix D. The energy uncertainties in equation E-3 are approximated as $\sigma(E(I) / E(I) \leq \pm 0.1\%$ and $\sigma(\overline{BE}) / \overline{BE} \leq \pm 0.5\%$.

Using these values in equation E-3 gives:

$$\frac{\sigma^2(Y(I))}{(Y(I))^2} \cong (0.15)^2 . \qquad \text{(E-4)}$$

It is noted that the relative uncertainty value in the intensity is the term that predominates in equation E-3.

Substituting the value of equation E-4 into E-2 gives:

$$\sigma^2(F) = \sum_I Y(I) \times Y(I) \; (0.15)^2 . \qquad \text{(E-5)}$$

The relative squared standard deviation of F is then given as:

$$\frac{\sigma^2(F)}{F^2} = \frac{\sum_I Y(I) \times Y(I) \; (0.15)^2}{\left\{\sum_I Y(I)\right\}^2} . \qquad \text{(E-6)}$$

Rewriting equation E-6, by expanding the denominator, gives:

$$\frac{\sigma^2(F)}{F^2} = \frac{\sum_I Y(I) \times Y(I) \; (0.15)^2}{\sum_I Y(I) \times Y(I) + 2 \sum_I \sum_{J>I} Y(I) \times Y(J)} . \qquad \text{(E-7)}$$

Thus:

$$\frac{\sigma^2(F)}{F^2} < \frac{\sum_I Y(I) \times Y(I) \; (0.15)^2}{\sum_I Y(I) \times Y(I)} = (0.15)^2 . \qquad \text{(E-8)}$$

Equation E-8 shows that the relative standard deviation of F is less than or equal to $\pm 15\%$, using the assumption that the uncertainties in the peak intensities are $\cong \pm 15\%$.

Appendix F Sensitivity of the GAMABC Analysis of the Continuum Region

Figure 3.3 of section 3.6.2, Chapter 3, has shown the general shape of the peak response function used in analysing the continuum data. Table F-1 summarizes the values of these response function parameters used for the pair spectrometer runs with the samples shown. These parameters have also been listed in the GAMABC parameters table given in the data chapters 4 - 9.

The summation values listed are taken from a lower channel number limit (IMAX) to channel number 4095, and are given in counts. The summation value of the continuum after subtracting the resolved gamma peaks is given, along with the summation value of the continuum at each stage of the analysis in which the continuum is corrected for the effects given in section 3.6. These three continuum summations values are given in table F-1 by the lines entitled: Peak Res. Cor., Background Cor., and Bin Res. Cor. The values of the three corrections are given in the lines entitled: Peak Res., Background, and Bin Res.

The fraction of the binding energy observed in the analysis of the spectra listed in table F-1 is shown beoken into four categories. These are: (1) Resolved Reg. PS, for the fraction due to the resolved peaks with energies greater than 1.5 MeV, (2) Resolved Reg. CS, for the fraction due to the resolved peaks with energies less

Table F-1 Summary of Peak Response Parameters and GAMABC Results for Samples Studied

Sample	Be	Fe	Nd	Sm	Eu	Gd	Er
Run No.	11141	11071	11211	11151	11221	11191	11261
Computer Run	J90401	J60323	J61326	J60276	J20052	J50029	J51203
Collimator (Inches)	1	1/2	1/2	1/2	1/2	1/2	1/2
Peak Response Parameters:							
F2	0.00120	0.00085	0.00085	0.00085	0.00085	0.00085	0.00085
F3	0.00070	0.00050	0.00040	0.00040	0.00045	0.00045	0.00045
F5	0.00230	0.00160	0.00140	0.00140	0.00150	0.00160	0.00150
F8	0.00660	0.00576	0.00420	0.00420	0.00450	0.00512	0.00450
Summations:							
Total Original	425915.0	1089260.0	1234535.0	894921.0	880280.0	1291321.0	1514593.0
Total Smoothed	425883.0	1089239.0	1234534.0	894930.0	880268.0	1291236.0	1514580.0
Peaks	55818.0	162887.0	151421.0	51793.0	33514.0	68547.0	68292.0
Continuum	387576.0	947265.0	1105114.0	869164.0	863880.0	1244673.0	1476308.0
After:							
Peak Res. Cor.	204789.1	399320.8	791347.1	806700.5	827195.3	1123716.0	1369381.0
Background Cor.	36191.9	204078.7	616835.2	634146.1	685133.7	951625.0	1202829.0
Bin Res. Cor.	3738.9	37521.1	216153.6	241300.2	233120.2	312426.7	405632.8
Corrections:							
Peak Res.	182839.1	548289.5	314406.4	62662.9	36875.6	120362.9	106350.0
Background	168592.4	195151.4	174420.6	172464.2	141980.2	173137.2	166524.7
Bin Res.	33935.1	167378.9	403121.0	396115.7	455742.2	643459.4	802341.9
%$\overline{BE}$ Calc:							
Resolved Reg. PS	100.9%	79.7%	26.9%	2.4%	1.2%	9.3%	6.5%
Resolved Reg. CS	3.4%	2.5%	14.8%	12.8%	0.5%	10.5%	9.5%
Unresol. Reg. PS	5.9%	18.5%	47.1%	66.6%	78.6%	78.0%	77.5%
Unresol. Reg. CS (est)	0.0%	0.0%	2.2%	4.6%	6.0%	9.8%	5.7%
Total % $\overline{BE}$	110.2%	100.7%	91.0%	86.4%	86.3%	107.6%	99.2%
$\overline{BE}$ (keV)	6811.9	7848.0	7480.0	7981.9	6294.8	8038.1	7638.0

than 1.5 MeV and greater than 200 keV, (3) Unresol. Reg. PS, for the fraction due to the unresolved gamma continuum with energy greater than 1.5 MeV, and (4) Unresol. Reg. CS (est), for the estimated fraction due to the unresolved gamma continuum with energy less than 1.5 MeV. The last two lines of table F-1 give the total fraction of average sample binding energy observed, and the value of the average binding energy used in the calculation.

The total fraction observed is within 100% ± 15% for all of the samples shown in table F-1. An indication of the total fraction observed from just the resolved peaks alone is given by summing the first two lines of the $\%\overline{E}$ calculation. This shows that less than 50% of the emitted energy is located in the yields of the resolved lines for the five rare earth samples studied.

The peak response function parameters are quite close to being equal to one another for the different samples. The one exception is the beryllium data, in which a 1 inch diameter collimator was used as compared to the use of a 1/2 inch diameter collimator for all the other samples shown. This larger collimator changed the geometry of the impinging gamma rays upon the Ge(Li) detector and consequently changed the response function of the detector.

Table F-1 also shows that the corrections to the continuum region are quite large, being on the order of several hundred thousand counts for each spectra shown. After the continuum

corrections have been made, the actual number of continuum counts converted to intensity due to unresolved gamma lines is usually on the order of 2 to 4 hundred thousand counts. The cases of beryllium and iron are shown in table F-1; these cases have also been discussed in section 3.6.2.

A computer experiment was performed on the neodymium data in order to determine the sensitivity of the results to the parameters used in the peak response function. Two additional computer runs were performed on the neodymium data, in which the peak response parameters were varied and all other parameters were kept the same. The results of these runs are compared with the GAMABC results described in Chapter 5 and are presented in table F-2 and F-3.

Table F-2 shows the parameters that were changed in each of the three runs, analysing the same Nd data spectrum. The total magnitudes of the continuum at various points of the analysis are listed in a form similar to that used in table F-1. For the low, medium, and high values of the peak response function, the observed fractions of the average binding energy, due to the unresolved gamma continuum with energy greater than 1.5 MeV, were 54.1%, 47.1% and 40.1% respectively.

Table F-3 presents the energy bin intensity from the unresolved gamma continuum in the neodymium sample for each of the three cases studied. The total intensities due to the resolved capture lines that lie within the energy bin are also given in table F-3. Changing the

Table F-2

Sensitivity of Peak Response Function for Neodymium Data

Sample	Nd	Nd	Nd
Run Number	11211	11211	11211
Computer Run	J11238	J61326	J11255
Peak Response (a) Parameters:	Low	Med	High
F2	0.00080	0.00085	0.00090
F3	0.00030	0.00040	0.00050
F5	0.00120	0.00140	0.00160
F8	0.00360	0.00420	0.00512
Summations: (b)			
Continuum:			
Total	1105114.0	1105114.0	1105114.0
After Peak Resp.	830635.5	791347.1	746354.1
After Background	653356.4	616835.2	574960.4
After Bin Resp. Corrections	248833.5	216153.6	183790.1
Corrections: (b)			
Peak Response	274978.9	314406.4	359553.1
Background	177187.0	174420.6	171305.2
Bin Response	406376.1	403121.0	394166.9
% $\overline{BE}$ Calculation			
Resolved Region			
PS	26.9%	26.9%	26.9%
CS	14.8%	14.8%	14.8%
Unresolved Region			
PS	54.1%	47.1%	40.1%
CS (est)	2.2%	2.2%	2.2%
Total % $\overline{BE}$	98.0%	91.0%	84.0%

(a) Peak response parameters: W1, W2, W3, LOW CH, and MID CH unchanged.

(b) Summations in counts from channel number IMAX to 4095.

Table F-3

Bin Intensities for Nd Using Three Peak Response Functions

Energy Bin (keV)	Intensity in Number of Photons/100 Captures Resolved Peaks	Peak Response Function LOW J11238	MED J61326	HIGH J11255
8000-8250	0.00	-0.10	-0.01	-0.02
7750-8000	0.00	-0.29	-0.27	-0.24
7500-7750	0.00	0.43	0.40	0.36
7250-7500	0.00	0.21	0.18	0.13
7000-7250	0.35	0.33	0.28	0.22
6750-7000	0.07	0.16	0.12	0.09
6500-6750	7.49	1.01	0.78	0.48
6250-6500	3.19	2.54	2.06	1.45
6000-6250	0.33	1.62	1.24	0.85
5750-6000	0.15	1.03	0.80	0.63
5500-5750	2.29	1.37	1.08	0.81
5250-5500	2.56	1.72	1.33	0.94
5000-5250	0.38	1.36	1.06	0.81
4750-5000	3.59	3.39	2.93	2.45
4500-4750	3.76	3.22	2.62	2.01
4250-4500	3.24	3.95	3.30	2.66
4000-4250	1.92	4.89	4.21	3.57
3750-4000	1.75	4.78	4.07	3.41
3500-3750	0.29	6.07	5.29	4.58
3250-3500	2.24	7.51	6.57	5.67
3000-3250	1.12	9.48	8.39	7.33
2750-3000	0.75	12.29	11.05	9.80
2500-2750	2.03	13.62	12.26	10.91
2250-2500	2.52	16.07	14.54	12.96
2000-2250	1.45	16.42	14.84	13.21
1750-2000	0.25	11.99	11.18	10.50
1500-1750	1.21	2.97	3.36	3.99

parameters by the values indicated in table F-2 changed the bin intensities by 10% to 20% as shown in table F-3. This compares to the 7% change experienced in the observed fraction of binding energy.

The results of table F-2 and F-3 indicate that it is desirable to know the peak response parameters to an accuracy of ± 10% in order to adequately analyse the continuum for the unresolved capture gamma lines present.

Appendix G Formats used in Tabular Presentation of Results

The results of the data analysis by computer have been given in the form of three tables, composed of computer output. Each of these three tables is described in this appendix.

The table which lists the GAMANL parameters, or which lists the GAMANL and GAMABC parameters, indicates the values used for the input parameters to the code, as well as listing some calculated output from the data. Table G-1 describes each line in this parameter table.

The results of analysing the well resolved peaks in the data are presented in the GAMANL results table. Each peak is labeled and its characteristics are studied. Table G-2 describes the column headings for this table.

Analysis of the continuum is performed by code GAMABC which uses the output from GAMANL. The results from the GAMABC analysis are presented in tabular form, in which the continuum is broken into bins of equal energy width, and each bin is analysed to determine the gamma intensity of the bin. Table G-3 describes the column headings for the GAMABC results table.

The last lines of the GAMABC results table give the fraction of average binding energy observed by using the listed energies and yields of the capture gamma data.

The average binding energy used in the calculation is given. The percent values for the continuum region of both positive and negative intensities are grouped together and their respective fractional values calculated and listed. The net sum of these two values is the fraction of binding energy which is due to the unresolved continuum with energy greater than 1.5 MeV. An average bin energy is used in weighting the intensity of each bin when performing the $\%\overline{BE}$ calculation on the unresolved continuum data.

The resolved peaks of the spectrum minus, the background peaks, contribute to the resolved percent of the binding energy observed. Only the resolved peaks that are listed in the above GAMABC table are used in this calculation.

A total percent observed is given by summing the two fractional results for the unresolved and the resolved data. Since this is pair spectrometer data, only gamma energies greater than 1.5 MeV are included in the $\%\overline{BE}$ calculations.

The three values listed above are labeled as: UNRES =, RES =, and TOTAL = , respectively.

The last line of the GAMABC results table gives the $\%\overline{BE}$ calculation values for gamma energies less than 1.5 MeV, and gives a total fraction observed for all gamma energies from 200 keV to 10.0 MeV. The unresolved continuum for energies less than 1.5 MeV is estimated by studying the

lower portion of the pair spectrometer continuum due to unresolved lines. The $\%\overline{BE}$ from the low energy (from 200 keV to 1.5 MeV) resolved peaks is calculated using the results of the GAMANL analysis on the Compton suppression data. Only the full energy peaks are used in the calculation, and the background peaks, so labeled in the GAMANL results for the Compton suppression data, are deleted from the calculation.

These values are expressed as CS UNRES (EST) = , CS RES = , and TOTAL ALL = , respectively.

Table G-1

Description of GAMANL, and GAMANL and GAMABC Parameters Table

Line:	Explanation:
1	Lists run number and number of channels in run.
2	Linearity run number; N2 and N3 are the lower and upper peaks that are used to make the linearity correction curve, peaks N2 and N3 are assumed to be correct and the other peaks are corrected for non-linearities with reference to N2 and N3; XN is the background level in counts, a linearity peak must have a peak height greater than XN in order to be analysed.
3	IMAX is the channel number at which analysis begins in the data spectrum.
4	DCR is the criterion for locating the minimum points of the spectrum and deciding whether to accept them as valid background points. See section 3.3.1 and 3.3.4.
5	PTS is the number of points (odd) used to average a data minimum point so as to obtain an accurate background level.
6	BGER is the peak height criterion input to the code, the peak height must be greater than BGER times the square root of the average background.
7	ECR gives the statistical error limit (in %) in the peak area, peaks with uncertainties in their area (one s.d. values) greater than ECR are not printed out.
8	In determining the least squares fit of the FWHM in keV to gamma energy in MeV, the initial FWHM value used is FPS, and the range that the least squares fit is allowed vary is ± ERFW in keV.
9	The energy per channel number is calculated by the code and listed here.

Table G-1 Continued

Line:	Explanation:
10-11	These lines present data on the two calibration peaks in the spectrum. The energy in keV, peak center actual in channel number, the peak center corrected for the system non-linearity in channel numbers, and the FWHM in keV are given for each calibration line.
12	The geometry factor SANGLE which is determined by the size of collimator used during the run is given; and FLUXT the total number of captures divided by 100 in the sample is given. These are discussed in section 3.4.
13	The energy dependent terms needed to calculate the peak intensities are stored in array EFFCY. The first EFFCY value stored corresponds to the energy value indicated, and the energy spacing in keV between EFFCY points is also given.
14-19 or 14-17	The values of the EFFCY array are listed beginning with the first stored value. Usually 28 values are used for Compton suppression data (energy spacing of 200 keV) and 19 values are used for the pair spectrometer data (energy spacing of 500 keV).
20 or 18	The number of peaks analysed, before applying the error ECR criterion, is listed. The computer job number beginning with J is printed out.
	In the cases when GAMABC is used, the following lines are added to the table.
19-26	The GAMABC peak response parameters are given. Chapter 3, section 3.6, discusses the terms: F2, F3, F5, F8, LOW CH, MID CH, W1, W2, and W3.
27	BAK FAC is the input factor which normalizes the background data to the sample data. Usually background run 11271 is used as the background spectrum. BIN WIDTH is the width of the bin in channel numbers used with the bin response correction for the unresolved lines. RED is the factor by which the total bin area is divided to approximate the bin area due to the unresolved peaks, RED corrects for the fact that each bin is sitting upon its own slight pedestal due to the shape of the peak response of the system.

Table G-2

Description of GAMANL Results Table

Column:	Heading:	Explanation:
1	PEAK NO	The number of the peak is given; if the peak is a background line, a B is placed before the number; the identification of the peak is given after the number; and X indicates that the peak is weak, or that there is uncertainty in assigning the peak to an element.
2	ENERGY KEV	The energy of the peak is given in keV.
3	PK CNT CH NO	The center of the peak in channel numbers is given. This is the measured peak center which is not corrected for the system non-linearities.
4	HEIGHT COUNTS	The height of the peak in counts as determined from the background calculation is given.
5	H TO B RATIO	The ratio of the peak height to the average background level under the peak is given.
6	AREA-S AREA-G COUNTS	The peak area as calculated by both area calculations is given. The area by the summation method is given on the first line, and the area by the Gaussian method is given directly below on the second line.
7	ERR-S ERR-G PCSD	The errors for the peak area are calculated as per Appendices A and B. The percent relative standard deviation (for one s.d.) is given on the first line for summation method, and on the second line for the Gaussian method.
8	INT-S INT-G N/100C	The intensity of the peak is calculated using each of the area values. The first line gives the intensity obtained using the summation area; the second line gives the intensity value obtained by using the Gaussian area. The intensity (or yield) is given in number of photons, of energy given in Column 2, observed per 100 captures in the sample.

Table G-2 Continued

Column:	Heading:	Explanation:
9	FWHM-M FWHM-C KEV	The full width at half maximum of the peak as measured is given in keV. Directly below is the FWHM as calculated from the least squares fit on the strong singlets of the spectrum. For peaks which are not singlets, just the FWHM for the least squares fit is given on both lines. See Column 12 explanation.
10	EFF(E) N/CTS	The efficiency value of the system at the peak energy is given. This includes system efficiency, and any other energy corrections, such as sample self-absorption, etc. EFF(E) is obtained by a second order interpolation from the three closest energy points in the EFFCY array.
11	BASE CHAN	The base of the peak in channel numbers is given. BASE = N-1=LUP - LO as discussed in section 3.3.2.
12	TYPE	The type of the peak is indicated: S for singlet peaks; S* for singlet peaks used in the least squares fit of the FWHM to gamma energy; D for doublet peaks, the value after the D is the Gaussian exponential value evaluated for the separation of the two peak heights; T for triplet peaks, the two values after the T are the values of the Gaussian exponentials for the two side peaks separated from the middle peak. These exponential values give the contribution of the neighboring peak height to the peak height being studied, and indicate the degree of overlap in the multiplet being analysed.

In the cases when a series of peaks is found to be a multiplet of order greater than three, a line is printed signifying the order of the multiplet, and the three strongest peaks in the multiplet are considered as triplet data.

Table G-3

Description of GAMABC Results Table

Column:	Heading:	Explanation:
		The first line of each page of the GAMABC table indicates the width of the energy bin used in keV, and gives the page number of the table.
1	BIN NO	The number of the bin, starting from the low energy (1.5 MeV) side, is given.
2	L CH NO	The channel number corresponding to the low energy side of the bin is given.
3	BIN AR COUNTS	The net bin area in counts due to unresolved gamma rays is given. Directly below this value is given the total positive number of counts in the bin.
4	BKGND AR COUNTS	The total counts in the bin that were due to background from the facility is given. These counts have been subtracted from the total continuum counts for this energy bin. Directly below the background total, is the total negative number of counts in the bin. The positive and negative totals for the bin are added together to give a net bin area which is the value listed in the first line of Column 3.
5	LEC AR COUNTS	The total number of counts in the bin that were due from higher energy resolved or unresolved lines is given. This value represents the total correction to the continuum of this bin that was due from the system response. The lines of columns 3 + 4 + 5 give the total number of counts that were in the continuum of this energy bin as recorded by the spectrum.
6	ENERGY KEV	The first line gives the low energy side value of the bin energy (keV). Any additional lines listed represent capture lines whose energies fall within the bin being studied. The energy values of the gamma lines are indented one space with reference to the energy value for the low energy side of the bin.

Table G-3 Continued

Column:	Heading:	Explanation:
7	INT N/100C	The first line gives the bin intensity of the unresolved capture lines in number of photons emitted with energies which lie within the energy width of the bin per 100 captures in the sample. Any additional lines gives the peak intensity for the peaks with energy as given in Column 6. The peak intensity values are indented one space with reference to the bin intensity value. The last line, which is indented two spaces from the bin intensity value, gives the total intensity of the resolved lines which lie within the bin being studied.
8	ERR PCSD	This column gives error estimates in the bin area value, and in the unresolved peak area values. The error is expressed in percent relative standard deviation of the area values (for one s.d.). In some cases listed, its value is large due to the fact that the error is divided by the net bin area, which in some cases is quite small. This listed error is an estimate only, and does not reflect the uncertainties in treating the continuum with the response functions, etc. The resolved peak errors listed are those obtained from the GAMANL analysis.

The last lines of table G-3 give the calculations for the fraction of the average binding energy observed as calculated using the above gamma energies and yields. The text of Appendix G discusses these lines in greater detail.

Appendix H Fortran IV Listing of GAMABC Code

The Fortran IV listing of the GAMABC code is given in the next two tables. Table H-1 gives the listing of MAIN and lists all of the subroutines associated with the continuum analysis section of GAMABC.

Table H-2 lists all of the subroutines that comprise the GAMANL section of GAMABC. All of the subroutines are listed except that of FOURT, the subroutine which performs the fast Fourier transform on the data. Subroutine FOURT is available from the IBM Program Information Department, 40 Sawmill River Road, Hawthorn, New York 10532, or by using MATHLIB, a subroutine library, on the MIT, IBM S/360 Model 65 computer.

Table H-3 gives a typical listing of the input deck required by GAMABC. Table H-4 shows the input parameters required on the input card number as shown. The input FORMAT used is also given.

The compilation time for GAMABC on the MIT M-65 system is about 1.50 minutes, execution time with data smoothing and punched output is about 1.70 minutes, and execution using smoothed data input is about 1.50 minutes.

```
C      GAMABC FORTRAN IV LISTING    GAMMA SPECTRAL ANALYSIS PROGRAM
C      GAMABC - MAIN
       COMPLEX DATA(4096)
       REAL TBK(4096),TBL(4096),DTS(4096),WT(4100),CNTR(200),CORR(200),
      1 EFFCY(100)
       REAL DATOR(4096),DATBK(4096)
C
       JREAD = 5
       JPRINT = 6
       JPUNCH = 7
C      LINEARITY CALCULATION
 2001  CONTINUE
       READ (JREAD,200) LR,NOCHAN,N2,N3,XN,LIN
  200  FORMAT (4I5,F5.0,I5)
C      LR        LINEARITY RUN NUMBER.
C      NOCHAN    NUMBER OF CHANNELS IN THE LINEARITY RUN, NOCHAN LEQ 4095.
C      N2        LOW CHANNEL PEAK NUMBER USED IN LINEARITY CALC.
C      N3        HIGH CHANNEL PEAK NUMBER USED IN LINEARITY CALC.
C      XN        BACKGROUND SUBTRACTION LIMIT USED FOR LINEARITY CALC.
C      LIN LEQ ZERO USES PREVICUSLY CALC. LINEARITY DATA.
C      IF LIN LEQ ZERO NOCHAN IS THE NUMBER OF PEAKS IN CNTR AND CORR
       IF (LIN) 131,131,101
  101  CONTINUE
       READ (JREAD,100) (TBL(I),I=1,NOCHAN)
  100  FORMAT (7X,7(F6.0,1X)/(8(F6.0,1X)))
C      TBL       LINEARITY DATA ARRAY
C      SUBROUTINE LINEAR CALCULATES THE CENTERS AND CORRECTION FACTORS
C      FOR THE LINEARITY DATA PEAKS.
             CALL LINEAR (TBL,CNTR,CORR,LR,N2,N3,XN,NOCHAN,JPRINT,JPUNCH)
       GO TO 2002
  131  CONTINUE
       WRITE  (JPRINT,152)
  152  FORMAT ('1',14X,' CNTR ARRAY',5X,' CORR ARRAY')
       DO 132 M=1,NOCHAN
```

```
      READ (JREAD,133) CNTR(M),CORR(M)
  133 FORMAT (19X,F7.2,9X,F7.2)
      WRITE (JPRINT,151) M,CNTR(M),CORR(M)
  151 FORMAT (' ',4X,I5,9X,F7.2,9X,F7.2)
  132 CONTINUE
 2002 CONTINUE
C     WT ARRAY DATA READ IN.
      READ (JREAD,1012) SIG1,MWTLO1,WTC1,WTF1,SIG2,MWTLO2,WTC2,WTF2
 1012 FORMAT (F5.0,I5,2F5.2,F5.0,I5,2F5.2)
C     SIG1 IS USED AS THE SIGMA IN WT FOR SMOOTHING
C     MWTLO1 IS USED AS THE CHANNEL NO AT WHICH THE SMOOTHING BEGINS
C     IF MWTLO1 IS LEQ ZERO NO SMOOTHING IS DONE.
C     SIG2 IS THE SIGMA USED FOR WT IN IMP RES. CASE
C     MWTLO2 IS THE CHANNEL NO ABOUT WHICH THE IMP RES TAKES EFFECT.
C     MWTLO2 SHOULD BE LARGER THAN 3*SIG2 TO KEEP J1 FROM BEING LEQ 0.
C     IF MWTLO2 IS LEQ 0 NO IMP RES IS DONE.
C     WTC1 AND WTF1 ARE CONSTANTS USED IN WT SMOOTHING.
C     WTC2 AND WTF2 ARE CONSTANTS USED IN WT IMPROVED RESOLUTION
 2003 CONTINUE
      READ (JREAD,121) J2,FIRENG,DELENG
  121 FORMAT(I5,2F5.0)
C     J2      NUMBER OF POINTS IN THE EFFCY ARRAY
C     FIRENG IS THE FIRST ENERGY (KEV) VALUE USED IN EFFICIENCY CALC.
C     DELE IS THE ENERGY (KEV) DIFFERENCE BETWEEN EFFICIENCY POINTS.
C     EFFCY   EFFICIENCY DATA ARRAY.
      READ (JREAD,120) (EFFCY(I),I=1,J2)
  120 FORMAT (7E10.3)
C     DATA READ IN
 2004 CONTINUE
      READ (JREAD,1001) NUMRUN,NOCHAN,IMAX,DCR,ECR,BGER,IPUNCH,PTS,
     1 SANGLE,FLUXT,NCUT
 1001 FORMAT (3I5,3F5.1,I5,F5.1,2E10.4,I5)
C     NUMRUN  THE DATA RUN NUMBER.
C     NOCHAN  NUMBER OF CHANNELS IN THE DATA RUN.
```

```
C      USUSALLY NOCHAN = 2**N - 1
C      IMAX     CHANNEL NUMBER SLOPE CRITERION, CHANNELS LEQ IMAX ARE NOT
C      ANALYZED.
C      DCR      SLOPE CRITERION USED FOR BACKGROUND CALCULATION.
C      ECR      ERRCR CRITERION USED IN SUBROUTINE PKANAL.
C       BGER IS THE NUMBER OF S.D. ABOVE THE BACKGROUND THAT A PKHT
C           SHOULD BE IN ORDER TO BE ACCEPTED AS A PEAK IN BAKSUB.
C      IPUNCH LESS THAN ZERO PUNCHES OUT PEAK ANALYSIS DATA
C      IPUNCH EQUAL ZERO IMPLIES NO PUNCHED OUTPUT.
C      IPUNCH EQUAL 1 PUNCHES OUT THE SMOOTHED DATA
C      IPUNCH EQUAL 2 PUNCHES OUT THE SMOOTHED, BACKGROUND SUBTRACTED DATA
C      IPUNCH EQUAL 3 PUNCHES OUT THE IMPROVED RESOLUTION DATA.
C      PTS IS THE ODD NO. CF POINTS USED TO AVERAGE THE MINIMA IN BAKSUB.
C      SANGLE IS THE SOLID ANGLE CORRECTION TERM
C      FLUXT IS THE NUMBER OF CAPTURES/100 IN THE SAMPLE.
C      NOUT = 0 PRINTS ALL, NOUT = 1 LIMITS THE PRINTING.
       READ (JREAD,100) (TBK(I),I=1,NOCHAN)
C      TBK IS THE DATA ARRAY
       NUM = NOCHAN + 1
C      NUM SHOULD BE A POWER OF TWO FOR FASTEST RESULTS.
       TBK(NUM) = 0.0
       SUMOR = 0.0
       DO 1520 I = IMAX,NOCHAN
C      SUMOR IS THE SUM OF NOCHAN-IMAX CRIGINAL DATA POINTS.
 1520  SUMOR = SUMOR + TBK(I)
       IF (NOUT.EQ.1) GO TO 170
       WRITE (JPRINT,1014) NUMRUN
 1014  FORMAT (1H1,4X,25H ORIGINAL DATA OF RUN NO ,I5)
       LK = NOCHAN/10
       DO 1501 J = 1,LK
       JU = J*10
       JL = JU - 9
C      JU IS THE CHANNEL NUMBER FOR EVERY TENTH POINT
       WRITE (JPRINT,1500) (TBK(I), I=JL,JU),JU
```

```
 1500 FORMAT(2X,10(F9.2,2X),I6)
 1501 CONTINUE
      JA = JU+1
      WRITE (JPRINT,1502) (TBK(I),I=JA,NOCHAN)
 1502 FORMAT(2X,10(F9.2,2X))
      GO TO 170
  162 CONTINUE
C     STATEMENTS 162 - 169 PUNCH OUT THE TBK ARRAY AT VARIOUS STAGES IN THE
C     PROGRAM .  IPUNCH DETERMINES WHAT IS PUNCHED OUT.
C     IPUNCH = 1,2, OR 3
      LO = 1
      LUP = 7
      WRITE (JPUNCH,163) (TBK(K),K=LO,LUP),LUP
  163 FORMAT (7X,7(F7.0),I6)
  164 CONTINUE
      LO = LUP + 1
      LUP = LUP + 8
      IF (LUP-NOCHAN) 165,165,166
  165 WRITE (JPUNCH,167) (TBK(K),K=LO,LUP),LUP
  167 FORMAT(8(F7.0),I6)
      GO TO 164
  166 CONTINUE
      IF (IPUNCH - 1) 168,1523,168
  168 IF (IPUNCH - 2) 169,1525,169
  169 IF (IPUNCH - 3) 170, 142,2010
  170 CONTINUE
C
C     START OF SMOOTHING OF TBK
C     MWTLO1 CRITERION ON SMOOTHING, MWTLO1.LE.0 IMPLIES NO SMOOTHING.
      IF (MWTLO1.LE.0) GO TO 160
C     CALCULATION OF THE WEIGHTING ARRAY WT.
      DO 134 I=1,NUM
  134 WT(I) = WTC1 + WTF1
      SIGSQ = SIG1*SIG1
```

```
      NUP = NUM/2
      DO 135 I=MWTLO1,NUP
      WTPO = (FLOAT(I - MWTLO1) * FLOAT(I - MWTLO1))/SIGSQ
      WT(I) = WTC1 + WTF1 * EXP(-WTPO/2.0)
  135 CONTINUE
C       SUBROUTINE CTFFT PERFORMS THE COOLEY-TUKEY FAST FOURIER TRANSFORM
C     CTFFT CALCULATES THE FOURIER TRANSFORM, FILTERS THE TRANSFORMED
C     DATA WITH WT AND PERFORMS THE INVERSE TRANSFORM.
C     CTFFT USES THE FACT THAT WT IS SYMMETRIC, ONLY NUM/2 PTS ARE USED.
C     THE INPUT ARRAY TBK IS REPLACED BY THE FILTERED DATA AT OUTPUT.
C
            CALL CTFFT (DATA,TBK,WT,NUM,JPRINT)
C
      IF (NOUT.EQ.1) GO TO 1523
      WRITE (JPRINT,1015) NUMRUN,SIG1,MWTLO1,WTC1,WTF1
 1015 FORMAT ('1',4X,' SMOOTHED DATA OF RUN NO ',I5,' SIG1 = ',F6.0,
     1 ' MWTLO1 = ',I5,' WTC1 = ',F5.2,' WTF1 = ',F5.2)
      DO 1503 J = 1,LK
      JU = J*10
      JL = JU - 9
      WRITE (JPRINT,1504) (TBK(I),I=JL,JU),JU
 1504 FORMAT(2X,10(F9.2,2X),I6)
 1503 CONTINUE
      JA = JU+1
      WRITE (JPRINT,1502)(TBK(I),I=JA,NOCHAN)
      IF (IPUNCH-1) 1523,1521,1523
 1521 GO TO 162
 1523 CONTINUE
      SUMSM = 0.0
      DO 157 I=IMAX,NOCHAN
  157 SUMSM = SUMSM + TBK(I)
      GO TO 161
  160 CONTINUE
      SUMSM = SUMCR
```

```
      SUMOR = 0.0
  161 CONTINUE
C
C     BACKGROUND SUBTRACTION AND PEAK LOCATION.
C
           CALL BAKSUB (TBK,TBL,DTS,WT,NOCHAN,DCR,PTS,BGER,NI,JPRINT,
     1 IMAX)
C     SUBROUTINE BAKSUB PERFORMS THE BACKGROUND SUBTRACTION ON THE TBK ARRAY
C     ARRAY TBL STORES THE BACKGROUND VALUES, DTS STORES THE FIRST DIFFERENCES
C     OF THE ORIGINAL DATA, AND WT(I+2100) STORES THE LOCATION OF THE I-TH PK.
C     THERE ARE A TOTAL OF NI PEAKS ANALYSED.
C     DCR IS BACKROUND MINIMA CRITERIA.  .
C     NEW MINIMA.LE.LAST MINIMA + DCR*SQRT(AVBK) + 10.0
C     PTS IS THE ODD NO. OF POINTS USED IN AVERAGING THE MINIMA.
C     BGER IS THE CRITERION ON THE PEAK HEIGHT. HT.GE.BGER*SQRT(AV BK) + 10.
C     STORING THE SMOOTHED BACKGROUND CALCULATED DATA IN DATOR ARRAY
C     FOR USE LATER AFTER PKANAL .
      DO 3001 I = 1,NOCHAN
      DATOR(I) = TBL(I)
      IF (I.LT.IMAX) DATOR(I) = 0.0
 3001 CONTINUE
      NIPK = NI
      IF (NOUT.EQ.1) GO TO 1525
      WRITE (JPRINT,154) NUMRUN
  154 FORMAT ('1',' CALCULATED BACKGROUND OF RUN NO ',I5)
      LLO = 1
      LUP = 10
  155 CONTINUE
      WRITE (JPRINT,1504) (TBL(I), I=LLO,LUP),LUP
      LLO = LLO + 10
      LUP = LUP + 10
      IF (LUP - NOCHAN) 155,156,156
  156 CONTINUE
      WRITE (JPRINT,1502) (TBL(I), I=LLO,NOCHAN)
```

```
      WRITE (JPRINT,1016) NUMRUN
 1016 FORMAT ('1',4X,'SMOOTHED BACKGROUND SUBTRACTED DATA RUN NO ',I5)
      DO 1506 J = 1,LK
      JU = J*10
      JL = JU - 9
      WRITE (JPRINT,1507) (TBK(I),I=JL,JU),JU
 1507 FORMAT(2X,10(F9.2,2X),I6)
 1506 CONTINUE
      JA = JU+1
      WRITE (JPRINT,1502) (TBK(I), I=JA,NOCHAN)
      IF (IPUNCH-2) 1525,1524,1525
 1524 GO TO 162
 1525 CONTINUE
      SUMBG = 0.0
      SUMBK = 0.0
      DO 153 I = IMAX,NOCHAN
C     SUMBG IS THE SUM OF NOCHAN-IMAX SMOOTHED BACKGROUND SUBTRACTED
C     DATA POINTS.
      SUMBG = SUMBG + TBK(I)
C     SUMBK IS THE SUM OF NOCHAN-IMAX BACKGROUND DATA POINTS.
      SUMBK = SUMBK + TBL(I)
  153 CONTINUE
      WRITE (JPRINT,550)
  550 FORMAT ('1',4X,' SUMATIONS FROM IMAX ')
      WRITE (JPRINT,551) SUMOR
  551 FORMAT(1HO,4X, 30H TOTAL COUNTS IN ORIGINAL DATA, F10.0)
      WRITE (JPRINT,552) SUMSM
  552 FORMAT(1HO,4X, 30H TOTAL COUNTS IN SMOOTHED DATA, F10.0)
      WRITE (JPRINT,553) SUMBK
  553 FORMAT(1HO,4X, 30H TOTAL BACKGROUND COUNTS      , F10.0)
      WRITE (JPRINT,554) SUMBG
  554 FORMAT ('0',4X,' TOTAL COUNTS IN SM-BKSUB DATA',F10.0)
C
C     IMPROVED RESOLUTION SECTION
```

```
C       IF MWTLO2 IS LEQ 0 NO IMP RES IS DONE.
        IF (MWTLO2) 142,142,143
  143 CONTINUE
        NUM2 = NUM/2
        DO 136 I = 1,NUM2
        WT(I) = WTC2
  136 CONTINUE
C       CALCULATION OF WT FOR IMPROVED RESOLUTION CASE.
        SIGSQ = SIG2*SIG2
        MSIG = SIG2
        NUP = MWTLO2 + 3 * MSIG
C       NUP MUST BE LESS THAN 2100 SINCE WT(2100+I) STORES THE LOCATION OF
C       THE I-TH PEAK AS CALC IN BAKSUB.
        DO 137 I = MWTLO2,NUP
        WTPO = FLOAT(I-MWTLO2)*FLOAT(I-MWTLO2)/SIGSQ
        WT(I) = WTC2 + WTF2 * EXP(-WTPO/2.0)
        J1 = MWTLO2 - I + MWTLO2
        WT(J1) = WT(I)
  137 CONTINUE
C       CTFFT USES THE FACT THAT THE WT ARRAY IS SYMMETRIC, AND ONLY NUM/2 PTS.
C       ARE NEEDED.
C
              CALL CTFFT (DATA,TBK,WT,NUM,JPRINT)
C
C       NEGLECTING ALL CHANNELS WITH COUNTS LEQ 20.0.
C        CALCULATING FIRST DIFF. ARRAY FOR NEW TBK ARRAY.
        TBK(NUM) = 0.0
        DO 138 I = 1,NOCHAN
        DUM = TBK(I) - 20.0
        IF (DUM) 139,139,138
  139 TBK(I) = 0.0
  138 DTS(I) = TBK(I+1) - TBK(I)
        WRITE (JPRINT,140) NUMRUN
  140 FORMAT ('1',4X,' SMOOTHED , BACKGROUND SUBTRACTED, IMPROVED RESOLU
```

```
     1TION DATA OF RUN NO ',I5)
      WRITE (JPRINT,150) SIG2,MWTLO2,WTC2,WTF2
  150 FORMAT (' ',4X,' SIG2 = ',F5.0,5X,' MWTLO2 = ',I5,5X,' WTC2 = ',
     1 F5.2,5X,'WTF2 = ',F5.2)
      DO 141 J=1,LK
      JU = J * 10
      JL = JU - 9
      WRITE (JPRINT,1507) (TBK(I),I=JL,JU),JU
  141 CONTINUE
      JA = JU + 1
      WRITE (JPRINT,1502) (TBK(I),I=JA,NOCHAN)
      IF (IPUNCH-3) 142,144,142
  144 GO TO 162
  142 CONTINUE
C
C     CALIBRATION OF DATA USING TWO ENERGY STANDARDS.
      READ (JREAD,1002) EGAM1,IP1,EGAM2,IP2,FPS,ERFW
 1002 FORMAT (4X,F6.1,4X,I6,4X,F6.1,4X,I6,3X,F7.2,3X,F7.2)
C     EGAM1 IS THE ENERGY (KEV) OF THE FIRST CALIB.PEAK.
C     EGAM1 LEQ ZERO DELETES ANALYSIS OF THE GAMMA PEAKS.
C     IP1 IS THE PEAK CENTER OF THE FIRST PEAK.
C     EGAM2 IS THE ENERGY (KEV) OF THE SECOND CALIB. PEAK.
C     IP2 IS THE PEAK CENTER OF THE SECOND PEAK.
C     FPS IS THE FIRST PEAK SIGMA USED IN PKANAL TO FIT THE FWHM.
C     FPS LEQ 0 IMPLIES FPS = FWHM OF FIRST CALIB.PEAK.
C     ERFW IS THE RANGE THE FWHM IS ALLOWED TO DEVIATE FROM FPS.
C     FPS AND ERFW ARE GIVEN IN KEV.
      IF (EGAM1) 2010,2010,145
  145 CONTINUE
C
           CALL PKALIB (TBK,DTS,CNTR,CORR,NOCHAN,EGAM1,IP1,EGAM2,IP2,
     1 SLP,WID1,WID2,TPC1,TPC2)
C     SUBROUTINE PKALIB CALCULATES THE FWHM, TRUE PEAK CENTERS OF THE
C     CALIBRATION PEAKS, ANS SLP TO CONVERT FROM CHANNEL NO. TO ENERGY.
```

```
C     PKALIB USES ADJUST TO CORRECT FOR THE NONLINEARITY OF THE SYSTEM.
C
      SLPOR = SLP
      TPCOR1 = TPC1
C     PRINT OUT OF INPUT DATA USED FOR ANALYSIS.
      WRITE (JPRINT,122) NUMRUN, NOCHAN
  122 FORMAT ('1',//////21X,'PARAMETERS AND INPUT DATA FOR RUN ',I5,
     1 2X,I4,' CHANNELS')
      WRITE (JPRINT,1018) LR,N2,N3,XN
 1018 FORMAT ('0',20X,'LINEAR RUN ',I5,' N2 = ',I3,' N3 = ',I3,' XN = ',
     1 F5.1)
      WRITE (JPRINT,123) IMAX
  123 FORMAT (' ',20X,'LOW CHANNEL NUMBER WHICH BEGINS ANALYSIS (IMAX)',
     1 I5)
      WRITE (JPRINT,125) DCR
  125 FORMAT (' ',20X,'BACKGROUND CRITERION DCR * SQRT(BK) DCR = ',F5.1)
      WRITE (JPRINT,158) PTS
  158 FORMAT (' ',20X,'NUMBER OF POINTS USED TO AVERAGE MINIMA = ',F5.1)
      WRITE (JPRINT,1020) BGER
 1020 FORMAT (' ',20X,'PEAK MAXIMA CRITERION, PKHT.GT.BGER*SQRT(BK)',
     1 ' BGER = ',F5.1)
      WRITE (JPRINT,126) ECR
  126 FORMAT (' ',20X,'PERCENT RELATIVE STANDARD DEVIATION CRITERION ',
     1 'ECR = ',F5.1)
      WRITE (JPRINT,1019) FPS,ERFW
 1019 FORMAT (' ',20X,'FIRST PEAK FWHM(KEV) FPS =',F6.2,' FWHM RANGE ',
     1 'ERFW =',F6.2)
      WRITE (JPRINT,130) SLP
  130 FORMAT (' ',20X,'ENERGY PER CHANNEL NUMBER (KEV) =',F6.3)
      WRITE (JPRINT,128) EGAM1,IP1,TPC1,WID1
  128 FORMAT (' ',20X,'CALIB1 E =',F6.1,' CNTR =',I5,' CORR =',F6.1,
     1 ' FWHM =',F6.2)
      WRITE (JPRINT,129) EGAM2,IP2,TPC2,WID2
  129 FORMAT (' ',20X,'CALIB2 E =',F6.1,' CNTR =',I5,' CORR =',F6.1,
```

```
     1 ' FWHM =',F6.2)
       WRITE (JPRINT,149) SANGLE,FLUXT
  149 FORMAT (' ',20X,'GEOMETRY FACTOR =',E10.3,' NO OF CAPT/100 =',
     1 E10.3)
       WRITE (JPRINT,147) FIRENG,DELENG
  147 FORMAT (' ',20X,'FIRST EFFCY ENERGY(KEV) ',F5.0,' DELTA ENERGY',
     1 '(KEV) ',F5.0)
       WRITE (JPRINT,148) (EFFCY(I),I=1,J2)
  148 FORMAT ((' ',20X,5(E10.3)))
       WRITE (JPRINT,159) NIPK
  159 FORMAT (' ',20X,'NUMBER OF PEAKS ANALYSED =',I3)
C
C      ANALYSIS OF THE GAMMA PEAKS
C
            CALL WIDLSQ (TBK,TBL,DTS,WT,CNTR,CCRR,EFFCY,FPS,WID1,PTS,
     1 SLP,EGAM1,TPC1,ERFW,ARATT,NIPK,JPRINT)
C      SUBROUTINE WIDLSQ PERFORMS A LEAST SQUARES FIT OF THE MEAS FWHM
C      TO A SECOND ORDER EQUATION IN ENERGY(MEV).
C
C      PKANAL PERFORMS THE ANALYSIS ON THE PEAKS.
            CALL PKANAL (TBK,TBL,DTS,WT,CNTR,CCRR,EFFCY,SLP,TPC1,EGAM1,
     1 ECR,ARATT,FIRENG,DELENG,SANGLE,FLUXT,PTS,NIPK,JPRINT,JPUNCH,
     2 IPUNCH)
  146 CONTINUE
C
C      BACKGROUND CALCULATION SECTION
C      READING IN PARAMETERS FOR DATBK ARRAY.
       READ (JREAD,3002) NBRUN,NBCHAN,E1,ARB1,E2,ARB2,E3,ARB3,DE
 3002 FORMAT (2I5,6F10.1,F5.2)
       IF (NBRUN)  3100,3100,3021
 3021 CONTINUE
C      NBRUN IS THE RUN NUMBER OF THE BACKGROUND DATA.
C      NBCHAN IS THE NO OF CHANNELS IN THE BACKGROUND DATA ARRAY.
C      NBCHAN  SHOULD EQUAL NOCHAN.
```

```
C     E1,ARB1, ETC. ARE THE ENERGIES AND AREAS IN KEV AND COUNTS FOR
C     THREE PEAKS IN THE BACKGROUND RUN WHICH ARE USED TO NORMALIZE WITH
C     PEAKS IN THE ORIGINAL DATA TBK.
C     THESE THREE PEAKS SHOULD ALSO APPEAR IN THE DATOR DATA ARRAY.
C     DE IS THE RANGE IN KEV WITHIN WHICH TWO PEAKS ARE CONSIDERED EQUAL.
C     READING IN THE BACKGROUND DATA ARRAY DATBK.
      READ (JREAD,100) (DATBK(I),I=1,NBCHAN)
      READ (JREAD,3003) EGAMB1,SLPB,TPCB1,NSBKP,FAC,PKBFAC,PFAC,MPUN
 3003 FORMAT (F10.2,F10.3,F10.2,I5,2F10.4,F5.2,I5)
C     EGAMB1 IS THE ENERGY OF THE FIRST CALIBRATION PEAK OF DATBK.
C     SLPB IS THE SLOPE KEV/CH OF THE DATA IN DATBK.
C     TPCB1 IS THE TRUE PEAK CENTER OF THE FIRST CALIB PEAK IN BK.
C     NSBKP IS THE NUMBER OF SPECIAL BACKGROUND PEAKS READ IN NEXT.
C     FAC IS THE FACTOR RELATING DATOR AND DATBK.
C     MPUN = 1 PUNCHES OUT DATOR ARRAY AFTER CORRECTIONS ARE DONE.
C     PKBFAC IS THE CORRECTION FACTOR FOR LOW ENERGY BACKGROUND FROM A
C     HIGHER ENERGY PEAK.  PKBFAC * PK AREA IS THE COUNT CONTRIBUTION PER CH.
      DO 3023 I = 1,100
      WT(I) = 0.0
 3023 CONTINUE
      IF (FAC.GT.0.0) GO TO 3010
C
           CALL BFAC (WT,E1,ARB1,E2,ARB2,E3,ARB3,DE,FAC,NIPK)
C     S.R. BFAC CALCULATES THE FACTOR RELATING DATOR TO DATBK BY USING
C     DATA FROM THREE PEAKS AND SUMMING THEIR RESPECTIVE AREAS IN BOTH ARRAYS.
 3010 CONTINUE
      FACTOR = FAC
      IF (FACTOR.LE.0.0) GO TO 2010
C
C     PRINT OUT OF INPUT BACKGROUND DATA.
      WRITE (JPRINT,3013)
 3013 FORMAT ('1',38X,'BACKGROUND  INPUT AND CALCULATED PARAMETERS')
      WRITE (JPRINT,3014) NBRUN,DE
 3014 FORMAT ('0',4X,'BACKGROUND RUN NO = ',I5,5X,'ENERGY DIFFERENCE ',
```

```
     1 'ALLOWED = DE(KEV) = ',F5.2)
       WRITE (JPRINT,3015) E1,ARB1,E2,ARB2,E3,ARB3
 3015 FORMAT ('0',4X,'ENERGY AND AREA USED FOR FACTOR CALC',
     1  6(2X,F10.2))
       WRITE (JPRINT,3016) WT(11),WT(1),WT(12),WT(2),WT(13),WT(3)
 3016 FORMAT ('0',4X,'ENERGY AND AREA  FROM GAMANL        ',
     1  6(2X,F10.2))
       WRITE (JPRINT,3017) FACTOR
 3017 FORMAT ('0',4X,'FACTOR FOR BACKGROUND RUN = ',E10.4)
       WRITE (JPRINT,3042) PKBFAC
 3042 FORMAT ('0',4X,'PEAK CONTRIBUTION TO LOW ENERGY BKGND FACTOR = ',
     1 ' PK AREA * PKBFAC WHERE PKBFAC = ',F10.4)
C
C      CORRECT DATBK FOR THE NSBKP BACKGROUND PEAKS THAT ARE READ IN.
C      LOOP 3007 DOES THE CORRECTING WITH J THE DUMMY VARIABLE.
C      TITLE TO PRINT OUT OF BACKGROUND PEAKS USED.
       WRITE (JPRINT,3019) NSBKP
 3019 FORMAT ('0',4X,'BACKGROUND PEAK CORRECTIONS, NO OF PEAKS = NSBKP',
     1 ' = ',I5)
       J = 1
       IPK = 1
       JPK = 1
       SUMB = 0.0
       LOUM = 3
 3007 CONTINUE
       IF (J.GT.NSBKP) GO TO 3008
       READ (JREAD,3004) ENGY,LOB,LUPB,BLO,BLUP,ABK
 3004 FORMAT (F10.1,2I5,3F10.1)
C      DO LOOP 3011 FINDS THE BACKGROUND PEAKS OF ENGY IN THE ORIGINAL
C      DATA, AND NOTES THAT THEY ARE BACKGROUND PEAKS BY ASSIGNING
C      A NEGATIVE SIGN TO THEIR ENERGY.
       EEPK = 0.0
       DO 3011 I=IPK,NIPK
       EPK = WT(I+2500)
```

```
C      PEAK ENERGY STORED MUST BE .LE. + OR - DE(KEV) OF ENGY TO BE
C      CONSIDERED AS THE SAME BACKGROUND PEAK.
       TEST = ABS(ENGY-EPK) - DE
       IF (TEST) 3012,3012,3011
 3012 CONTINUE
       EEPK = EPK
       JPK = I
       WT(I+2500) = (-1.0) * WT(I+2500)
       ADAT = WT(I+3700)
       GO TO 3022
 3011 CONTINUE
 3022 CONTINUE
       IPK = JPK
C      DO LOOP 3006 FITS DATBK BETWEEN LOB AND LUPB WITH THE VALUES READ IN.
       DO 3006 I = LOB,LUPB
       DATBK(I) = (BLO*(LUPB-I) + BLUP*(I-LOB))/(LUPB-LOB)
 3006 CONTINUE
       CH = (LOB + LUPB)/2.0
       AREA = ABK
       CALL PCB (DATBK,ENGY,CH,AREA,PKBFAC,PFAC,SUMB,IMAX,NOCHAN,LDUM)
C      S.R. PCB CORRECTS THE BACKGROUND DATA FOR LOW ENERGY CONTINUUM
C      FROM HIGHER ENERGY PEAKS.
C
C      PRINT OUT OF THE PEAK BEING ERASED.
       WRITE (JPRINT,3018) EEPK,ADAT
 3018 FORMAT (' ',4X,'DATA BACKGROUND E(KEV)=',F10.1,50X,' AREA = ',
      1 F10.1)
       WRITE (JPRINT,3020) ENGY,LOB,LUPB,BLO,BLUP,ABK
 3020 FORMAT (' ',4X,'BACKGROUND      E(KEV)=',F10.1,' CH NOS = ',2I5,
      1 ' COUNTS = ',2F10.1,' AREA = ',F10.1)
       J = J + 1
       GO TO 3007
 3008 CONTINUE
C      END OF LOOP FOR BACKGROUND PEAKS.
```

```
C     READING IN BIN WIDTH, BINDING ENERGY LEVEL, BIN LOW ENERGY
C     FACTOR, AND BIN WIDTH USED IN LOW ENERGY CONTINUUM CORRECTION.
C     BPFAC IS BIN PEDESTAL FACTOR USED IN PCB.
      READ (JREAD,3009) BINWID,BINDE,BINFAC,BPFAC,IWIT
 3009 FORMAT (2F10.2,F10.5,F5.2,I5)
      NOCHAN = NBCHAN
C
C     SUBROUTINE BFIT FITS DATBK TO DATOR IN TERMS OF ENERGY BY USING THE
C     CALIBRATION DATA READ INTO THE SUBROUTINE.
C     SLPOR AND SLPB ARE THE SLOPES KEV/CH OF THE ARRAYS.
C     TPCOR1 AND TPCB1 ARE THE TRUE PEAK CENTERS OF THE FIRST CALIB PEAK.
C     NOCHAN IS THE NUMBER OF CHANNELS IN DATBK.
           CALL BFIT(DATBK,DTS,FACTOR,EGAM1,EGAMB1,SLPOR,SLPB,TPCOR1,
     1                TPCB1,NCCHAN)
C
C     CORRECTING FOR THE LOW ENERGY CONTRIBUTION FROM A HIGHER ENERGY PEAK.
C     SUBTRACTING THE NORMALIZED BACKGROUND DATBK FROM THE ORIG. DATA DATOR.
      SUMB = SUMB * FACTOR
           CALL BPKCOR (DATOR,DATBK,WT,PKBFAC,PFAC,SUMB,NOCHAN,
     1                  IMAX,NIPK)
C
C     SUBROUTINE BNCOR CALCULATES THE LOW ENERGY CONTINUUM DUE TO A HIGHER
C     ENERGY BIN CONTRIBUTION.
C     IWIT IS THE WIDTH OF THE BIN IN CH. NOS. USED FOR THE CORRECTION.
C     BINFAC IS USED AS THE FACTOR RELATING TO THE BIN AREA.
           CALL BNCOR (DATOR,BINFAC,BPFAC,EGAM1,SLPOR,TPCOR1,NOCHAN,
     1                 IMAX,IWIT)
C
C     PRINT OUT OF DATOR ARRAY, AND THEN CORRECTION FOR NEGATIVE VALUES.
      WRITE (JPRINT,3027)
 3027 FORMAT ('1',4X,'DATOR ARRAY AFTER BACKGROUND SUBTRACTION OF ',
     1 'DATBK ARRAY')
      LLO = 1
      LUP = 10
```

```
 3028 CONTINUE
      WRITE (JPRINT,3029) (DATOR(I),I=LLO,LUP),LUP
 3029 FORMAT (2X,10(F9.2,2X),I5)
      LLO = LLO + 10
      LUP = LUP + 10
      IF (LUP.GE.NOCHAN) GO TO 3030
      GO TO 3028
 3030 CONTINUE
      WRITE (JPRINT,3031) (DATOR(I),I=LLO,NOCHAN)
 3031 FORMAT (2X,10(F9.2,2X))
C
C     PUNCH OUT OF DATOR ARRAY IF MPUN IS EQUAL TO 1.
      IF (MPUN - 1) 3038,3039,3038
 3039 CONTINUE
      LO = 1
      LUP = 7
      WRITE (JPUNCH,163) (DATOR(I),I=LO,LUP),LUP
 3040 CONTINUE
      LO = LUP + 1
      LUP = LUP + 8
      IF (LUP-NOCHAN) 3041,3041,3038
 3041 WRITE (JPUNCH,167) (DATOR(I),I=LO,LUP),LUP
      GO TO 3040
 3038 CONTINUE
C
C     ENERGY BIN CALCULATION IS DONE BY SUBROUTINE BINS.
      WRITE (JPRINT,3037) BINWID,BINDE
 3037 FORMAT ('0',4X,'BIN WIDTH(KEV) =',F10.2,'  BINDING ENERGY(KEV) =',
     1 F10.2)
C      BINWID IS THE BIN WIDTH IN KEV.
C     BINWID MUST DIVIDE DELENG EVENLY, I.E. AN INTEGER AMOUNT.
C     BINDE IS THE BINDING ENERGY OF THE ELEMENT BEING STUDIED.
C
           CALL BINS (TBL,DATOR,DATBK,DTS,WT,EFFCY,BINWID,BINDE,FIRENG,
```

```
     1                DELENG,SANGLE,FLUXT,EGAM1,SLPOR,TPCOR1,NOCHAN,
     2                IMAX,NIPK,NBINS)
C      SUBROUTINE BINS CALCULATES THE INTENSITY PER BIN OF THE RESOLVED
C      AND UNRESOLVED REGION.  THE FRACTION OF OBSERVED GAMMAS ARE ALSO
C      CALCULATED USING THE BINDING ENERGY.
C      END OF BACKGROUND  AND BIN DETERMINATION SECTION.
C
 3100 CONTINUE
      READ (JREAD,1008) MO
 1008 FORMAT (I5)
      GO TO (2001,2002,2003,2004), MO
C     MO=1 PROGRAM LOOPS TO 2001,MO=2 PROGRAM LOOPS TO 2002, ETC.
C     MO.LEQ.0 OR MO.GTR.4 ENDS PROGRAM BY GOING TO 2010
 2010 CONTINUE
      CALL EXIT
      END
      SUBROUTINE BFAC (WT,E1,ARB1,E2,ARB2,E3,ARB3,DE,FAC,NIPK)
      REAL WT(4100)
C     S.R. BFAC CALCULATES THE FACTOR RELATING DATOR TO DATBK BY USING
C     DATA FROM THREE PEAKS AND SUMMING THEIR RESPECTIVE AREAS IN BOTH ARRAYS
C
      DO 7 I=1,100
      WT(I) = 0.0
    7 CONTINUE
      I = 1
      J = 0
      ES = E1
C     LOOP 1 SEARCHES WT(I+2500) ARRAY FOR THE ES ENERGY.
    1 IF (I.GT.NIPK) GO TO 3
      TEST = ABS(WT(I+2500) - ES) - DE
C     WT(I+2500 IS THE STORED ENERGY OF THE I-TH PEAK OF BAKSUB.
C     DE IS THE ALLOWABLE DEVIATION THAT WT(I+2500) CAN HAVE FROM ES AND
C     STILL BE CONSIDERED THE SAME PEAK.
      IF (TEST.LT.0.0) GO TO 2
```

```
      I = I + 1
      GO TO 1
    2 J = J + 1
      WT(J) = WT(I+3700)
      WT(J+10) = WT(I+2500)
C     WT(I+3700) IS THE AREA OF THE I-TH PEAK WHOSE ENERGY IS WT(I+2500)
      IF (J.EQ.1) ES = E2
      IF (J.EQ.2) ES = E3
      IF (J.EQ.3) GO TO 3
      I = I + 1
      GO TO 1
    3 CONTINUE
      IF (WT(2).LE.0.0) ARB1 = 0.0
      IF (WT(2).LE.0.0) ARB2 = 0.0
      IF (WT(3).LE.0.0) ARB3 = 0.0
      ARB = ARB1 + ARB2 + ARB3
      IF (ARB) 4,4,5
    5 CONTINUE
      FAC = (WT(1) + WT(2) + WT(3))/ARB
      GO TO 6
    4 CONTINUE
      FAC = 1.0
    6 CONTINUE
      RETURN
      END
      SUBROUTINE BFIT(DATBK,DTS,FACTOR,EGAM1,EGAMB1,SLPOR,SLPB,TPCOR1,
     1                TPCB1,NOCHAN)
      REAL DATBK(4096),DTS(4096)
C     SUBROUTINE BFIT FITS DATBK TO DATOR IN TERMS OF ENERGY BY USING THE
C     CALIBRATION DATA READ INTO THE SUBRCUTINE.
C     EGAM1 AND EGAMB1 ARE THE ENERGIES OF THE FIRST CALIB. PEAK.
C     SLPOR AND SLPB ARE THE SLOPES KEV/CH OF THE ARRAYS.
C     TPCOR1 AND TPCB1 ARE THE TRUE PEAK CENTERS OF THE FIRST CALIB PEAK.
C     NOCHAN IS THE NUMBER OF CHANNELS IN DATBK.
```

```
      A = (EGAM1 - EGAMB1) / SLPB
      RS = SLPB/SLPOR
      DO 1 I = 1,NOCHAN
C     DTS IS USED AS A DUMMY ARRAY TO TEMPORARILY STORE THE SHIFTED VALUES
C     OF THE THE DATBK ARRAY.
      B = I
      K = A + RS * (B - TPCCR1) + TPCB1 + 0.5
      IF (K.LE.0) GO TO 2
      IF (K.GT.NOCHAN) GO TO 2
      DTS(I) = DATBK(K) * FACTOR
      GO TO 1
    2 DTS(I) = -1.0
    1 CONTINUE
      DO 3 I = 1,NOCHAN
      DATBK(I) = DTS(I)
    3 CONTINUE
      RETURN
      END
       SUBROUTINE BPKCOR (DATOR,DATBK,WT,PKBFAC,PFAC,SUMB,NOCHAN,
     1                    IMAX,NIPK)
      REAL DATOR(4096),DATBK(4096),WT(4100)
C     S.R. BPKCOR CORRECTS DATOR FOR THE LOW ENERGY CONTRIBUTION TO THE
C     BACKGROUND FROM A HIGHER ENERGY PEAK.
C     PKBFAC IS USED TO MAKE THE CORRECTION PER CH. NO.
C     PFAC IS USED TO DETERMINE THE PEDESTAL HEIGHT UNDER A PEAK.
C
      SUMO = 0.0
      SUMOP = 0.0
      SUMON = 0.0
      SOR = 0.0
      SORP = 0.0
      SORN = 0.0
      SBCOR = 0.0
      SBK = 0.0
```

```
      SUMB = SUMB * 1.35 * 1.35
C
C     CORRECTION FOR LOW ENERGY CONTRIBUTION FROM HIGHER ENERGY PEAKS.
      DO 3032 I = 1,NIPK
      EPK = WT(I+2500)
      IF (EPK) 3033,3032,3033
 3033 CONTINUE
      ENGY = EPK
      CH = WT(I+2100)
      AREA = WT(I+3700)
      LDUM = 1
      CALL PCB (DATOR,ENGY,CH,AREA,PKBFAC,PFAC,SBCOR,IMAX,NOCHAN,LDUM)
 3032 CONTINUE
C
C     SUBTRACTION OF DATBK ARRAY FROM DATOR ARRAY.
      DO 3045 I = 1,IMAX
      DATOR(I) = 0.0
      DATBK(I) = 0.0
 3045 CONTINUE
      DO 3023 I = IMAX,NOCHAN
      IF (DATBK(I).EQ.(-1.0)) DATBK(I) = DATOR(I)
      IF (DATOR(I)) 3050,3051,3051
 3051 SUMOP = SUMOP + DATOR(I)
      GO TO 3052
 3050 SUMON = SUMON + DATOR(I)
 3052 CONTINUE
      DATOR(I) = DATOR(I) - DATBK(I)
      IF (DATOR(I)) 3053,3054,3054
 3054 SORP = SORP + DATOR(I)
      GO TO 3055
 3053 SORN = SORN + DATOR(I)
 3055 CONTINUE
      SBK = SBK + DATBK(I)
 3023 CONTINUE
```

```
      SOR = SORP + SORN
      SUMO = SUMOP + SUMON
C
C     PRINT OUT OF SUM DATA FROM IMAX
      WRITE (6,3047) SUMOP,SUMON,SUMO
 3047 FORMAT ('0',4X,'SUM OF DATOR, CORR FOR PEAK LE CONT ',2F10.1,
     1 ' = ',F10.1)
      WRITE (6,3042) SORP,SORN,SOR
 3042 FORMAT ('0',4X,'SUM OF DATOR, CORR FOR DATBK AND PEAK LE CONT ',
     1  2F10.1,' = ',F10.1)
      WRITE (6,3043) SBK
 3043 FORMAT ('0',4X,'SUM OF NORMALIZED DATBK ARRAY FROM IMAX ',F10.1)
      WRITE (6,3046) SUMB
 3046 FORMAT ('0',4X,'SUM OF NORMALIZED PEAK LE CONT.IN DATBK ',F10.1)
      WRITE  (6,3056) PKBFAC,PFAC
 3056 FORMAT ('0',4X,'PEAK RESPONSE FUNCTION, PKBFAC = ',F8.4,
     1 ' PFAC = ',F5.2)
      WRITE (6,3044) SBCCR
 3044 FORMAT ('0',4X,'SUM OF LOW ENERGY CONTRIBUTION FROM HIGHER ',
     1 'ENERGY PEAKS ',F10.1)
      RETURN
      END
      SUBROUTINE BINS (TBL,DATOR,DATBK,DTS,WT,EFFCY,BINWID,BINDE,FIRENG,
     1                 DELENG,SANGLE,FLUXT,EGAMI,SLPOR,TPCORI,NOCHAN,
     2                 IMAX,NIPK,NBINS)
      REAL TBL(4096),DATOR(4096),DATBK(4096),DTS(4096),WT(4100),
     1 EFFCY(100)
C     SUBROUTINE BINS CALCULATES THE INTENSITY PER BIN OF THE RESOLVED
C     AND UNRESOLVED REGION.  THE FRACTION OF OBSERVED GAMMAS ARE ALSO
C     CALCULATED USING THE BINDING ENERGY.
C     BINWID MUST DIVIDE DELENG EVENLY, I.E. AN INTEGER AMOUNT.
C     BINWID IS THE BIN WIDTH IN KEV.
C     BINDE IS THE BINDING ENERGY OF THE ELEMENT BEING STUDIED.
C
```

```
      NPUN = 1
C     NPUN = 1 PUNCHES OUT THE BIN DATA AS PER FORMAT STATEMENT 11.
      LCT = 0
      LPG = 0
C     SUBROUTINE BGTOP PUTS THE TITLE ON THE PRINTED OUTPUT FROM BINS.
            CALL BGTOP(LCT,LPG,BINWID)
      IEF = 2
C     IEF IS USED WITH EFFCY ARRAY FOR INTENSITY CALCULATION.
      NO = 1
      NEF = DELENG/BINWID
C     NO AND NEF ARE USED TO ADVANCE IEF FOR EFFCY CALC.
C     BINWID MUST DIVIDE DELENG WITH AN INTEGER VALUE.
      K = 0
C     K IS DUMMY VARAIABLE USED TO STORE THE NUMBER OF BINS USED.
      JPK = 1
      IPK = 1
C     IPK KEEPS TRACK OF WHICH PEAK WAS USED LAST IN ENERGY, WT(I+2500) CALC.
      E = FIRENG
C     FIRENG IS THE FIRST ENERGY POINT IN THE EFFCY ARRAY.
C     CALC THE LOWER AND UPPER ENERGY LIMITS OF THE DATOR.
      CHAN = NOCHAN
      PMAX = IMAX
      EFIRST = EGAM1 + SLPOR * (PMAX-TPCOR1)
      ELAST = EGAM1 + SLPOR * (CHAN-TPCOR1)
C
C     SETTING E TO BE .GE. EFIRST.
    3 IF (E-EFIRST) 2,4,4
    2 E = E + BINWID
      NO = NO + 1
      IF (NO-NEF) 3,3,19
   19 IEF = IEF + 1
      NO = 1
      GO TO 3
    4 CONTINUE
```

```
C      LO IS THE LOW CH NO CONSIDERED.
       LO = (E-EGAM1)/SLPOR + TPCOR1 + 0.5
C      LOOP 5 IS THE BIN CALCULATION SECTION.
C      LO IS THE CH NO CORRES TO E, LOW ENERGY OF BIN.
C      LUP IS THE CH NO CORRES. TO ENERGY EUP, HIGH E OF BIN.
C      DO LOOP 6 CALCULATES THE BIN AREAS FROM LO = LO + 1 TO LUP.
C     GIVING THE SUM FROM CH NOS WITH ENERGY.GT.E AND .LE. EUP.
     5 CONTINUE
       LO = LO + 1
       EUP = E + BINWID
       LUP = (EUP-EGAM1)/SLPOR + TPCOR1 + 0.5
       IF (LUP.GT.NOCHAN) LUP = NOCHAN
       NO = NO + 1
       IF (NO-NEF) 21,21,20
    20 IEF = IEF + 1
       NO = 1
    21 CONTINUE
       BAREAP = 0.0
       BAREAN = 0.0
       BPKAR = 0.0
       BBKAR = 0.0
       BERS = 0.0
       BINT = 0.0
       DO 6 I = LO,LUP
       IF (DATOR(I).GE.0.0) BAREAP = BAREAP + DATOR(I)
       IF (DATOR(I).LT.0.0) BAREAN = BAREAN + DATCR(I)
       BBKAR = BBKAR + DATBK(I)
       BPKAR = TBL(I) + BPKAR
     6 CONTINUE
       BERS = 2.0 * BPKAR - (BAREAP - BAREAN)
       BPKAR = BPKAR - BAREAP + BAREAN - BBKAR
       BAREA = BAREAP + BAREAN
       IF (BERS .LE.0.0) BERS = BAREA * BAREA
       IF (BAREA) 8,7,8
```

```
      7 BER = 100.0
        GO TO 9
      8 BER = SQRT(BERS) * 100.0 / ABS(BAREA)
      9 CONTINUE
C       INTENSITY CALCULATION USING EFFCY ARRAY, SANGLE, AND FLUXT
        EAV = E + BINWID/2.0
        G1 = EFFCY(IEF-1)
        G2 = EFFCY(IEF)
        G3 = EFFCY(IEF+1)
        H12 = (G2 - G1)/DELENG
        H23 = (G3 - G2)/DELENG
        H123 = (H23 - H12)/(2.0*DELENG)
        E2 = FIRENG + FLOAT(IEF-1) * DELENG
C       GX IS SECOND ORDER INTERPOLATED VALUE OF EFFCY  FOR ENERGY EAV.
        GX = G1 + (EAV-E2+DELENG)*H12 + (EAV-E2)*(EAV-E2+DELENG)*H123
        BINT = BAREA/(GX*SANGLE*FLUXT)
C       K IS THE BIN NUMBER
        K = K + 1
C       STORING THE BIN PARAMETERS IN DTS ARRAY.
        DTS(K+500) = E
        DTS(K+900) = BINT
        DTS(K+1300) = BER
        DTS(K+1700) = BAREA
        LCT = LCT + 1
        IF (LCT.GT.48) CALL BGTOP(LCT,LPG,BINWID)
        WRITE (6,10) K,LO,BAREA,BBKAR,BPKAR,E,BINT,BER
     10 FORMAT (' ',20X,I4,I5,3(F9.1),F8.1,F7.2,F6.1)
        IF (NPUN.EQ.1) WRITE (7,11) K,LO,BAREA,BBKAR,BPKAR,E,BINT,BER
     11 FORMAT (2I5,4F10.1,F10.2,F10.1)
C       SEARCH GAMANL OUTPUT DATA, WT, FOR PEAKS WITH ENERGY .GT. E AND
C       .LE. E + BINWID, IPK IS RETAINED AFTER SEARCH.
        PKINT = 0.0
        DO 13 I = IPK,NIPK
        EPK = WT(I+2500)
```

```
      IF (EPK - E) 13,13,14
   14 IF (EPK - (E+BINWID)) 15,15,13
   15 SINT = WT(I+500)
      ERAS = WT(I+1700)
      JPK = IPK + 1
      PKINT = PKINT + SINT
      LCT = LCT + 1
      IF (LCT.GT.48) CALL BGTOP(LCT,LPG,BINWID)
      WRITE (6,16) EPK,SINT,ERAS
   16 FORMAT (' ',57X,F8.1,F7.2,F6.1)
   13 CONTINUE
      IPK = JPK
      TINT = BINT + PKINT
      DTS(K+2100) = TINT
      LCT = LCT + 1
      IF (LCT.GT.48) CALL BGTOP(LCT,LPG,BINWID)
      WRITE (6,17) BAREAP,BAREAN,PKINT
   17 FORMAT (' ',29X,2F9.1,19X,F7.2)
      IF (EUP.GT.ELAST) GO TO 18
C     INCREASE PARAMETERS IN LOOP 5
C     E AND LO ARE THE ENERGY AND CH NO OF THE LOW SIDE OF THE NEXT BIN.
      E = EUP
      LO = LUP
C     LOOP TO 5 FOR NEXT BIN CALCULATION.
      GO TO 5
   18 CONTINUE
C     NBINS IS NUMBER OF BINS CALCULATED.
      NBINS = K
C
C     FRACTION OF OBSERVED GAMMA CALCULATION AND PRINT OUT.
      BIN2 = BINWID/2.0
      SUMUN = 0.0
      SUMUP = 0.0
      SUM2 = 0.0
```

```
      SUM3 = 0.0
      DO 22 K = 1,NBINS
      ENG = DTS(K+500) + BIN2
      BINT = DTS(K+900)
      IF (BINT.LT.0.0) SUMUN = SUMUN + ENG * BINT
      IF (BINT.GE.0.0) SUMUP = SUMUP + ENG * BINT
      SUM2 = SUM2 + ENG * DTS(K+2100)
   22 CONTINUE
      FRUP = SUMUP / BINDE
      FRUN = SUMUN / BINDE
      FR1 = FRUP + FRUN
      FR2 = SUM2/BINDE
      DO 23 I =1,NIPK
      EPK = WT(I+2500)
      IF (EPK) 23,23,24
   24 SUM3 = SUM3 + EPK * WT(I+500)
   23 CONTINUE
      FR3 = SUM3/BINDE
      IF (LCT.GT.44) CALL BGTOP(LCT,LPG,BINWID)
      WRITE (6,25)
   25 FORMAT ('0',22X,'FRACTION OF GAMMA RAYS OBSERVED')
      WRITE (6,26) BINDE
   26 FORMAT (' ',22X,'AVERAGE BINDING ENERGY (KEV) = ',F8.2)
      WRITE (6,27) FRUP,FRUN,FR1,FR3,FR2
   27 FORMAT (' ',22X,'UNRES = ',2F5.1,' = ',F5.1,' RES = ',F5.1,
     1 ' TOTAL = ',F5.1)
C
      RETURN
      END
      SUBROUTINE BGTOP(LCT,LPG,BINWID)
C     SUBROUTINE BGTOP PUTS THE TITLE ON THE PRINTED OUTPUT FROM BINS.
      LCT = 3
      LPG = LPG + 1
      WRITE (6,1) BINWID,LPG
```

```
    1 FORMAT ('1',////22X,'ENERGY INTERVAL ANALYSIS BIN WIDTH =',
     1 F7.1,' KEV  PAGE ',I3)
       WRITE (6,2)
    2 FORMAT (' ',20X,' BIN L CH   BIN AR BKGND AR   LEC AR  ENERGY',
     1 '    INT   ERR')
       WRITE (6,3)
    3 FORMAT (' ',20X,'  NO   NO   COUNTS   COUNTS   COUNTS     KEV',
     1 ' N/100C  PCSD')
       RETURN
       END
       SUBROUTINE PCB (DAT,ENGY,CH,AREA,PKBFAC,PFAC,SUMB,IMAX,
     1 NOCHAN,LDUM)
       REAL DAT(4096)
C      SUBROUTINE PCB CORRECTS THE CONTINUUM FOR THE PEAK RESPONSE FUNCTION.
C      THE F FACTORS ARE THE MAGNITUDE IN UNITS OF PEAK AREA FOR THE
C      RESPONSE FUNCTION AT DIFFERENT CHANNELS IN THE SPECTRUM.
C      THE L FACTORS ARE THE CHANNEL NUMBERS FOR DIFFERENT REGIONS OF THE
C      SPECTRUM.
C      LCH IS THE CH NO OF THE PEAK CENTER, OR THE BIN CENTER.
       LCH = CH
       IF (LCH.LE.IMAX) GO TO 1
       IF (LCH.GE.NOCHAN) GO TO 1
C      ENGY IS THE ENERGY OF THE PEAK, OR BIN.
       IF (ENGY.LT.0.0) ENGY = (-1.0) * ENGY
C      L1 IS THE WIDTH OF THE LOW ENERGY SIDE PEDESTAL OF THE PEAK.
       IF (ENGY.GT.6810.0) L1 = 250.0+125.0*(ENGY-6800.0)/ 850.0
       IF (ENGY.LE.6810.0) L1 = 120.0+130.0*(ENGY-2200.0)/4610.0
C      AREA IS THE AREA IN COUNTS OF THE PEAK OR BIN.
       F2 = 0.0009 * AREA
       F3 = 0.0006 * AREA
       F4 = F2 + F3
C      PKBFAC IS THE FACTOR CONTROLLING THE CONTINUUM  OF THE PEAK.
       F5 = PKBFAC * AREA
       F6 = F5 - F4
```

```
C       PFAC IS THE FACTOR TIMES PKBFAC THAT CONTRCLS THE HEIGHT OF THE
C       PEDESTAL.  GENERALLY ARCUND .0065 * AREA.
        F7 = (PFAC-1.0) * F5
        F8 = F7 + F5
C       LUPW IS APPROX ONE HALF THE BASE WIDTH OF A STRONG PEAK.
        LUPW = 0.0004 * AREA + 2.0
        DUM = F3 / (900-IMAX)
        L2 = 900
        L3 = LCH - L1
        IF (L3.LE.IMAX) L3 = IMAX
        IF (L3 - L2) 7,7,8
    7   CONTINUE
        DO 9 J = IMAX,L3
        DAT(J) = DAT(J) - F2 - (J-IMAX) * DUM
    9   CONTINUE
        SUMB = SUMB +
       1 (F2+0.5*F3)*(L3-IMAX) + (F5+0.5*F7)*(L1) + F8*(LUPW+35)
        GO TO 10
    8   CONTINUE
        DO 2 J = IMAX,L2
        DAT(J) = DAT(J) - F2 - (J-IMAX) * DUM
    2   CONTINUE
        L2 = L2 + 1
        DUM = F6 / (L3 - L2)
        DO 3 J = L2,L3
        DAT(J) = DAT(J) - F4 - (J-L2) * DUM
    3   CONTINUE
        SUMB = SUMB +
       1 (F2+0.5*F3)*(L2-IMAX) + (F4+0.5*F6)*(L3-L2) + (F5+0.5*F7)*(L1) +
       2 F8*(LUPW+35)
   10   CONTINUE
        L3 = L3 + 1
        DUM = F7 / (L1)
        DO 4 J = L3,LCH
```

```
      DAT(J) = DAT(J) - F5 - (J-L3) * DUM
    4 CONTINUE
      L4 = LCH + 1
      L5 = LCH + LUPW
      IF (L5.GT.NCCHAN) L5 = NOCHAN
      DO 5 J = L4,L5
      DAT(J) = DAT(J) - F8
    5 CONTINUE
      L5 = L5 + 1
      L6 = L5 + 70
      IF (L6.GT.NCCHAN) L6 = NOCHAN
      L7 = 70 + L5
      DUM = F8 / 70.0
      DO 6 J = L5,L6
      DAT(J) = DAT(J) - (L7-J) * DUM
    6 CONTINUE
    1 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE BNCOR (DATOR,BINFAC,BPFAC,EGAM1,SLPOR,TPCOR1,NOCHAN,
     1                  IMAX,IWIT)
      REAL DATOR(4096)
C     SUBROUTINE BNCOR CALCULATES THE LOW ENERGY CONTINUUM DUE TO A HIGHER
C     ENERGY BIN CONTRIBUTION.
C     BINFAC IS USED AS THE FACTOR RELATING TO THE BIN AREA.
C     IWIT IS THE WIDTH OF THE BIN IN CH. NOS. USED FOR THE CORRECTION.
      SUMBC = 0.0
      LUP = NOCHAN
      LO = LUP - IWIT + 1
      WIT = IWIT
      CH = LUP + IWIT/2
      ENGY = EGAM1 + (CH + 0.5 - TPCOR1) * SLPOR
      LDUM = 2
C     LDUM = 2 INDICATES A BIN RESPONSE FOR SR PCB.
    4 CONTINUE
      BAR = 0.0
      DO 1 I = LO,LUP
      BAR = BAR + DATOR(I)
    1 CONTINUE
C     IWIT THE BIN WIDTH SHOULD BE EVEN
      MID = LO + IWIT/2
      ENGY = ENGY - WIT * SLPOR
      CH = MID
      IF (BAR) 12,12,13
   13 CONTINUE
      AREA = BAR / (1.00 + WIT * BINFAC * BPFAC)
      CALL PCB (DATOR,ENGY,CH,AREA,BINFAC,BPFAC,SUMBC,IMAX,NOCHAN,LDUM)
   12 CONTINUE
C     DECREASE LOOP PARAMETERS AND LOOP TO 4 FOR NEXT LOWER BIN.
      LUP = LO - 1
      LO = LUP - IWIT + 1
      IF (LO.LT.IMAX) LO = IMAX
      IF (LUP.LE.IMAX) GO TO 5
```

```
      GO TO 4
    5 CONTINUE
C     PRINT OUT BIN CORRECTION DATA
      WRITE (6,7) SUMBC
    7 FORMAT ('0',4X,'SUM OF LOW ENERGY CONTRIBUTION FROM HIGHER ',
     1 'ENERGY BINS ',F10.1)
C     PRINT OUT OF BIN LE CALCULATION DATA.
      WRITE (6,6) IWIT,BINFAC,BPFAC
    6 FORMAT ('0',4X,'BIN RESPONSE FUNCTION, BIN WIDTH (CHS) = ',I5,
     1 ' BINFAC = ',F8.5,' BPFAC = ',F5.2)
C     CALCULATING THE SUMS OF THE CH NOS IN DATOR ARRAY.
      SUMP = 0.0
      SUMN = 0.0
      DO 8 I = IMAX,NOCHAN
      IF (DATOR(I)) 10,11,11
   11 SUMP = SUMP + DATOR(I)
      GO TO 8
   10 SUMN = SUMN + DATOR(I)
    8 CONTINUE
      SUMT = SUMP + SUMN
      WRITE (6,9) SUMP,SUMN,SUMT
    9 FORMAT ('0',4X,'SUM OF DATOR CORRECTED FOR BIN LE CONTINUUM ',
     1  2F10.1,' = ',F10.1)
      RETURN
      END
```

```
C       FORTRAN IV LISTING
        SUBROUTINE LINEAR (TBL,CNTR,CORR,LR,N2,N3,XN,NOCHAN,JPRINT,JPUNCH)
        REAL TBL(4096),CNTR(200),CORR(200)
C       SUBROUTINE LINEAR CALCULATES THE LINEARITY CORRECTION FACTOR
C       USING THE LINEARITY DATA GIVEN IN ARRAY TBL.
C       THE CORRECTION FACTOR, CORR, IS IN THE FORM OF AN ARRAY OF
C       DIMENSION L (L LEQ 200) OF THE L LINEARITY PEAKS CHARACTERIZING
C       THE DATA OF TBL.
C       THE ADJUST SUBROUTINE USES THE CORR FACTCR FOR ITS INTERPOLATION
C       TO CORRECT FOR LINEARITY.
C       XN        IS THE LIMIT OF THE LINEARITY BACKGROUND.  ONLY TRUE
C                 CALIBRATION PEAKS ARE GTR THAN XN.
C       TBL       IS THE LINEARITY DATA.
C       N2        IS THE CHANNEL PEAK NO. OF THE LOW REFERENCE PEAK
C       N3        IS THE CHANNEL PEAK NO. OF THE HIGH REFERENCE PEAK.
C       CNTR(L)   IS THE PEAK CENTER AS CALC BY WEIGHTING THE FIRST MOMENT
C                 OF THE PEAK TO THE INTEGRAL UNDER THE PEAK.
C       CORR(L)   IS THE LINEARITY CORRECTION FACTOR FOR THE L-TH PEAK.
C       SUM       IS THE PEAK INTEGRAL.
C       XMOM      IS THE FIRST MOMENT OF THE PEAK.
C       SLOPE     IS THE LINEAR SLOPE BETWEEN THE N2 AND N3 PEAKS.
        J=0
        L=0
        I = 0
    3   I=I+J+1
        IF (I-NOCHAN) 31,7,7
   31   J=0
        IF (TBL(I)-XN) 3,3,4
    4   J=J+1
        IPLJ=I+J
        IF (IPLJ-NOCHAN) 12,7,7
   12   CONTINUE
        IF (TBL(IPLJ)-XN) 5,5,4
```

```
    5  SUM=0.
       XMOM=0.
       DO 6 K2=1,J
       K1=I+K2-1
       SUM=SUM+TBL(K1)
       XMOM=XMOM+FLOAT (K2)*TBL(K1)
    6  CONTINUE
       L=L+1
       IF (L-200) 13,7,7
   13  CONTINUE
       CNTR(L) = XMOM/SUM + FLOAT (I) - 1.0
       IF (I-NOCHAN) 3,7,7
    7  SLOPE=(CNTR(N3)-CNTR(N2))/FLOAT (N3-N2)
       WRITE (JPRINT,9) LR,N2,N3,XN
    9  FORMAT ('1',' LINEARITY RUN NUMBER ',I5,'  N2 = ',I5,'   N3 = ',
      1 I5,'   XN = ',F5.0)
       WRITE (JPRINT,10)
   10  FORMAT ('0',14X,' CNTR ARRAY     CORR ARRAY ')
       DO 8 M=1,L
       CORR(M)=(CNTR(N2)+FLOAT (M-N2)*SLOPE)-CNTR(M)
       WRITE (JPRINT,11) M,CNTR(M),CORR(M)
       WRITE (JPUNCH,11) M,CNTR(M),CORR(M)
   11  FORMAT (' ',4X,I5,9X,F7.2,9X,F7.2)
    8  CONTINUE
       RETURN
       END


       SUBROUTINE ADJUST (CNTR,CORR,PCNR,TPC)
       REAL CNTR(200),CORR(200)
C      SUBROUTINE ADJUST FINDS THE TRUE PEAK CENTER, TPC, BY CORRECTING
C      THE DATA PEAK CENTER, PCNR, BY GX.
C      GX IS DETERMINED BY A SECOND ORDER INTERPOLATION USING CNTR, THE
C      CALCULATED PEAK CENTER, AND CORR, THE LINEARITY CORRECTION FACTOR
```

```
C       FROM THE LINEARITY SUBROUTINE.
C       A CALL TO LINEAR MUST PRECEDE A CALL TO ADJUST.
        IOTA=1
   11   IF (CNTR(IOTA)-PCNR) 10,10,20
   10   IOTA=IOTA+1
        IF (IOTA.GT.200) GO TO 12
        GO TO 11
   20   G1=CORR(IOTA-1)
        G2=CORR(IOTA)
        G3=CORR(IOTA+1)
        C1=CNTR(IOTA-1)
        C2=CNTR(IOTA)
        C3=CNTR(IOTA+1)
        CX=PCNR
        IF (C2.LE.C1) GO TO 12
        IF (C3.LE.C2) GO TO 12
        IF (C3.LE.C1) GO TO 12
        D12=(G2-G1)/(C2-C1)
        D23=(G3-G2)/(C3-C2)
        D123=(D23-D12)/(C3-C1)
        GX = G1 + (CX-C1)*D12 + ((CX-C1)*(CX-C2)*D123)
        TPC=PCNR+GX
        GO TO 13
    12  CONTINUE
        TPC = PCNR
    13  CONTINUE
        RETURN
        END


        SUBROUTINE CTFFT (DATA,TBK,WT,NUM,JPRINT)
C       COOLEY-TUKEY FAST FOURIER TRANSFORM
        COMPLEX DATA(4096)
        REAL TBK(4096),WT(4096)
```

```
C       CTFFT TRANSFORMS THE ARRAY TBK, WEIGHTS IT WITH WT, AND PER-
C       FORMS THE INVERSE TRANSFORMATION.
C       DATA IS A COMPLEX ARRAY USED IN SUBROUTINE FOURT.
C       SUBROUTINE FOURT DOES THE ACTUAL FFT CALCULATION.
C       NUM SHOULD BE A POWER OF TWO FOR FASTEST RESULTS.
        DO 1 I = 1,NUM
        DATA(I) = CMPLX(TBK(I),0.0)
      1 CONTINUE
C
C       FAST FOURIER TRANSFORM ON DATA.
              CALL FOURT (DATA,NUM,1,+1,+1,0)
C
        DO 2 I = 1,NUM
        AR = REAL(DATA(I))
        AI = AIMAG(DATA(I))
        TBK(I) = SQRT(AR*AR + AI*AI)
C       TBK IS USED TO STORE THE MAGNITUDE OF EACH TRANSFORMED POINT.
      2 CONTINUE
        W = 6.2831873/FLOAT(NUM)
        NUM2 = NUM/2 + 2
C       PRINT OUT OF TRANSFORMED DATA.
        WRITE (JPRINT,3) W
      3 FORMAT (1H1,26H DELTA OMEGA IN RADIANS = ,F10.6)
        WRITE (JPRINT,4)
      4 FORMAT (1H ,19H TRANSFORM INTEGRAL)
        WRITE (JPRINT,5) (TBK(I),I=1,NUM2)
      5 FORMAT (1H ,10E11.4)
C       FILTERING THE TRANSFORMED DATA WITH WT(I).
        NUM2 = NUM/2
        DO 8 I = 1,NUM2
C       SMOOTHING
        J = NUM - I + 1
        DATA(I) = WT(I) * DATA(I)
        DATA(J) = WT(I) * DATA(J)
```

```
    8 CONTINUE
C
C     INVERSE FOURIER TRANSFORM
            CALL FOURT(DATA,NUM,1,-1,+1,0)
C
      DO 10 I = 1,NUM
      AR = REAL(DATA(I))
      AI = AIMAG(DATA(I))
      TBK(I) = SQRT(AR*AR + AI*AI)/FLOAT(NUM)
C     DIVIDING BY NUM IS TO CORRECTLY NORMALIZE THE OUTPUT DATA.
   10 CONTINUE
      RETURN
      END


      SUBROUTINE BAKSUB (TBK,TBL,DTS,WT,NOCHAN,DCR,PTS,BGER,NI,JPRINT,
     1 IMAX)
      REAL TBK(4096),TBL(4096),DTS(4096),WT(4100)
C     SUBROUTINE BAKSUB  CALCULATES AND STORES THE BACKGROUND DATA IN
C     ARRAY TBL.  THE BACKGROUND SUBTRACTED DATA IS STORED IN TBK.
C     THE PEAKS ARE LOCATED AND THE LOCATION STORED IN WT(2100+I)
C     DTS STORES THE FIRST DIFFERENCES OF TBK.
C     NOCHAN IS THE NUMBER OF DATA POINTS 2**N - 1.
C     DCR IS THE CRITERION FOR ACCEPTING A MINIMA AS BACKGROUND.
C     NEW MIN .LE. PREVIOUS MIN + DCR * SQRT(BK) + 10.0
C     PTS IS THE ODD NUMBER OF POINTS USED TO AVERAGE THE MINIMA.
C     BGER IS PEAK HEIGHT CRITERION.
C     PK HT .GE. BGER * SQRT(BK) + 10.0
C     NI IS THE TOTAL NUMBER OF PEAKS ACCEPTED FOR ANALYSIS.
C
      JJ = NOCHAN - 1
      DO 1 I = 1,JJ
      DTS(I) = TBK(I+1) - TBK(I)
      WT(I) = 0.0
```

```
      TBL(I) = 0.0
    1 CONTINUE
      TBL(NOCHAN) = 0.0
      WT(NOCHAN) = 0.0
C     LABEL FOR PRINT OUT.
      WRITE (JPRINT,32) DCR
   32 FORMAT ('1','  BACKGROUND SUBTRACTION CALCULATIONS - DCR = ',F5.1)
      WRITE (JPRINT,18)
   18 FORMAT ('0','  NO  L CH  LEFT MIN    RT MIN    PK MAX  MIN TEST',
     1 ' BASE   PTS AVG')
      LO = IMAX
      UALM = TBK(LO)
      TBL(LO) = UALM
      I = IMAX + 1
      NI = 0
      IAVL = 1
      NPTS = PTS
C     LOCATING THE PEAK MINIMA.
    2 CONTINUE
      IF (DTS(I)) 5,3,3
    3 IF (DTS(I-1)) 4,4,5
    4 CONTINUE
      LUP = I
      TEST = SQRT((TBL(LO) + TBK(LUP))/2.0)
      DUM = TBK(LUP) - DCR * TEST - 10.0 - TBL(LO)
C     DCR CRITERION ON NEXT MINIMA.
C     NEW MIN .LE. PREVIOUS MIN + DCR*SQRT(PREV. MIN) + 10.0
      IF (DUM) 6,6,5
    6 CONTINUE
C     AVERAGING THE ACCEPTED MINIMA TBK(LUP) ABOUT (PTS-1.0)/2.0 POINTS
C     ON EACH SIDE OF TBK(LUP) PROVIDED THEY ARE WITHIN ONE S.D. OF TBK(LUP)
      SUM = 0.0
      DIV = 0.0
      DO 7 J = 1,NPTS
```

```
      IJ = LUP -(NPTS+1)/2 + J
      IF (IJ.LE.IMAX) GO TO 7
      IF (IJ.GT.NOCHAN) GO TO 7
      IF (IJ-LO) 10,10,9
   10 DUM = TBL(IJ) - TBK(LUP) - TEST
      IF (DUM) 30,30,31
   30 DIV = DIV + 1.0
      SUM = SUM + TBL(IJ)
   31 GO TO 7
    9 DUM = TBK(IJ) - TBK(LUP) - TEST
      IF (DUM) 8,8,7
    8 DIV = DIV + 1.0
      SUM = SUM + TBK(IJ)
    7 CONTINUE
      IF (DIV.LE.0.0)  DIV = 1.0
      TBL(LUP) = SUM/DIV
      UAUM = TBK(LUP)
      TBK(LUP) = 0.0
C     TBL IS USED TO STORE THE BACKGROUND.
C     TBK WILL BE THE BACKGROUND SUBTRACTED ARRAY UPON LEAVING BAKSUB.
      IAVR = DIV
C     CALCULATING THE BACKGROUND BETWEEN LO AND LUP
      LBASE = LUP - LO
      IF (LBASE-1) 34,34,35
   35 CONTINUE
      BASE = FLOAT(LBASE)
      CTLIM = BGER * TEST + 10.0
C     CTLIM IS USED WITH BGER TO INSURE THAT PKHT IS ABOVE STATISTICS.
      K = LBASE - 1
C     DO LOOP 33 CALCULATES THE BACKGROUND BETWEEN LO AND LUP.
      DO 33 J = 1,K
      NLO = LO + J
      TBL(NLO) = (TBL(LO)*FLOAT(LUP-NLO)+TBL(LUP)*FLOAT(J))/BASE
      TBK(NLO) = TBK(NLO) - TBL(NLO)
```

```
   33 CONTINUE
C     DO LOOP 12 LOCATES THE PEAKS USING THE BGER CRITERION.
      DO 12 J = 1,K
      NLO = LO + J
      DTS(NLO)   = TBK(NLO+1) - TBK(NLO)
      DTS(NLO-1) = TBK(NLO) - TBK(NLO-1)
C     FINDING MAXIMUM
      IF (DTS(NLO)) 14,14,12
   14 IF (DTS(NLO-1)) 12,12,15
   15 CONTINUE
C     CRITERION ON PKHT
      IF (TBK(NLO) - CTLIM) 12,16,16
   16 CONTINUE
      NI = NI + 1
      IF (NI.GT.396) GO TO 27
C     WT(NI+2100) IS USED TO STORE THE LOCATION OF THE MAXIMUM OF THE I-TH PK.
      WT(NI + 2100) = FLOAT(NLO)
      WRITE (JPRINT,17) NI,LO,TBL(LO),TBL(LUP),TBK(NLO),TEST,LBASE,IAVL,
     1 IAVR
   17 FORMAT (' ',2I5,4(1X,F9.2),3I5)
   12 CONTINUE
C     END OF DO LOOP ON LOCATING THE PEAKS.
C
C     PUTTING BACK INTO BACKGROUND ARRAY, TBL, PEAKS THAT ARE TOO SMALL
C     TO BE ANALYSED AS PER THE BGER (CTLIM) CRITERION.
C
      IF ((WT(NI+2100)).GT.(FLOAT(LO))) GO TO 13
      TBL(LO) = UALM
      DO 11 J = 1,K
      NLO = LO + J
      TBL(NLO) = TBL(NLO) + TBK(NLO)
   11 CONTINUE
   13 CONTINUE
C
```

```
      GO TO 36
   34 CONTINUE
      TBL(LUP) = UAUM
   36 CONTINUE
      IAVL = IAVR
      UALM = UAUM
      LO = LUP
C
C     INCREASE I AND LOOP TO FIND THE NEXT MINIMA.
    5 CONTINUE
      I = I + 1
      IF (I - JJ) 2,2,19
   19 CONTINUE
      DO 20 J = LUP,NOCHAN
      TBL(J) = TBK(J)
      TBK(J) = 0.0
   20 CONTINUE
C     SETTING THE LIMITS OF 396 OR LESS PEAKS TO BE ANALYSED.
      IF (NI - 396) 26,26,27
   26 WT(NI + 2101) = NOCHAN
      WT(NI + 2102) = NOCHAN
      WT(NI + 2103) = NOCHAN
      GO TO 28
   27 NI = 396
      WT(2497) = NOCHAN
      WT(2498) = NOCHAN
      WT(2499) = NOCHAN
   28 CONTINUE
      DO 21 J = 1,IMAX
      TBL(J) = 0.0
      TBK(J) = 0.0
      DTS(J) = 0.C
   21 CONTINUE
      DO 29 J = IMAX,NOCHAN
```

```
      IF (TBL(J)) 23,24,24
   23 TBL(J) = 0.0
   24 CONTINUE
      IF (TBK(J)) 25,22,22
   25 TBK(J) = 0.0
   22 CONTINUE
      DTS(J) = TBK(J+1) - TBK(J)
   29 CONTINUE
      RETURN
      END


      SUBROUTINE PKALIB (TBK,DTS,CNTR,CORR,NOCHAN,EGAM1,IP1,EGAM2,IP2,
     1 SLP,WID1,WID2,TPC1,TPC2)
      REAL TBK(4096),DTS(4096),CNTR(200),CORR(200)
C     SUBROUTINE PKALIB CALCULATES THE FWHM, TRUE PEAK CENTERS OF THE
C     CALIBRATION PEAKS, ANS SLP TO CONVERT FROM CHANNEL NO. TO ENERGY.
C     PKALIB USES ADJUST TO CORRECT FOR THE NONLINEARITY OF THE SYSTEM.
      JP=0
      IP = IP1 - 3
  631 IF (DTS(IP)) 615,615,613
  615 IF (DTS(IP-1))613,613,617
  613 IP = IP + 1
      GO TO 631
  617 PCNR=FLOAT (IP)+DTS(IP)/(DTS(IP-1)-DTS(IP))+ 0.5
C     PCNR    IS PEAK CENTER.
C     GX I S A SECCND ORDER INTERPOLATION FIT.
      GX = 0.5*(TBK(IP) + (PCNR-FLOAT(IP))*(DTS(IP)) + 0.5 *
     1 (PCNR-FLOAT(IP))*(PCNR-FLOAT(IP+1))*(DTS(IP)-DTS(IP-1)))
C     SUBROUTINE ADJUST CALCULATES THE TRUE PEAK CENTER, TPC, USING
C     DATA FROM THE LINEARITY SUBROUTINE.
           CALL ADJUST (CNTR,CORR,PCNR,TPC)
      IF (JP) 620,620,621
C     TPC1    TRUE PEAK CENTER FOR THE LOW ENERGY STANDARD.
```

```
 620  TPC1=TPC
C     GX1      HALF MAXIMUM OF LOW ENERGY STANDARD.
      GX1=GX
      JP=JP+1
      IP = IP2 - 3
      GO TO 631
C     TPC2     TRUE PEAK CENTER FOR THE HIGH ENERGY STANDARD.
 621  TPC2=TPC
C     GX2      HALF MAXIMUM OF HIGH ENERGY STANDARD.
      GX2=GX
C     SLP      SLOPE USED TO CONVERT CHANNEL NUMBER TO ENERGY.
      SLP=(EGAM2-EGAM1)/(TPC2-TPC1)
      JP1=0
      GX=GX1
      NP=IP1
 669  J=NP
 672  IF (TBK(J)-GX) 670,670,671
 671  J=J-1
      GO TO 672
C     PHL      CHANNEL NUMBER OF LOW ENERGY SIDE FOR FWHM CALCULATION.
 670  PHL=FLOAT (J)+(GX-TBK(J))/(TBK(J+1)-TBK(J))
      J=NP
 682  IF (TBK(J)-GX) 680,680,681
 681  J=J+1
      GO TO 682
C     FWHM     FULL WIDTH AT HALF MAXIMUM.
 680  FWHM=FLOAT (J)-(GX-TBK(J))/(TBK(J-1)-TBK(J))-PHL
      WIDD = FWHM * SLP
C     WIDD IS FWHM IN KEV
      IF (JP1) 686,686,687
 686  WID1 = WIDD
C     WID1 IS FWHM (KEV) OF FIRST CALIB PEAK.
C     THE VARIANCE OF THE PEAK CAN BE OBTAINED FROM THE FWHM.
C     JP1 = 0 AT BEGINNING.
```

```
      GX=GX2
      JP1=JP1+1
      NP=IP2
      GO TO 669
 687  WID2 = WIDD
C     WID2 IS FWHM (KEV) OF SECOND CALIB PEAK.
      RETURN
      END


      SUBROUTINE WIDLSQ (TBK,TBL,DTS,WT,CNTR,CORR,EFFCY,FPS,WID1,PTS,
     1 SLP,EGAM1,TPC1,ERFW,ARATT,NI,JPRINT)
      REAL TBK(4096),TBL(4096),DTS(4096),WT(4100),CNTR(200),CORR(200),
     1 EFFCY(100)
C     SUBROUTINE WIDLSQ PERFORMS A LEAST SQUARES FIT OF THE MEAS FWHM
C     TO A SECOND ORDER EQUATION IN ENERGY(MEV).
C
C     LABEL FOR OUTPUT FROM WIDLSQ
      WRITE (JPRINT,1001)
 1001 FORMAT ('1',25X,' PEAKS USED IN COMPUTING LSQ FIT OF FWHM')
      WRITE (JPRINT,1002)
 1002 FORMAT ('0',4X,'NUMBER PK NO ENERGY KEV WIDTH KEV  S.D. KEV      W
     1EIT      PKHT AREAS/AREAG')
C     INITIAL VALUES SET EQUAL TO ZERO.
      WE0 = 0.0
      WE1 = 0.0
      WE2 = 0.0
      E0  = 0.0
      E1  = 0.0
      E2  = 0.0
      E3  = 0.0
      E4  = 0.0
      NUMPK = NI
      PTSAV = PTS
```

```
      AREASS = 0.0
      AREAGG = 0.0
      MM = 0.0
C     FPS EXPECTED FWHM (KEV) OF FIRST PEAK EITHER READ IN OR CALC.
      IF (FPS) 3034,3034,3035
 3034 FPS = WID1
C     WID1 IS FWHM (KEV) OF FIRST CALIB. PEAK.  CALC. IN PKALIB.
 3035 CONTINUE
      I = 0
      WT(2100) = 0.0
C
C     LOOP FOR LSQ FIT OF FWHM, END OF LOOP AT 2100.
 2000 CONTINUE
      I = I + 1
      IF (I - NUMPK) 2001,2001,2100
 2001 CONTINUE
C     WT(2500+I) IS ZERO FROM BAKSUB.    WIDLSQ WILL STORE PK ENERGY AT
C     THIS LOCATION FOR THOSE PEAKS USED IN FIT OF FWHM.
C     LHT IS CHANNEL NUMBER OF I-TH PEAK MAXIMUM.
      LHT = WT(2100 + I)
C     ERROR TERM CRITERIA FOR LSQ FIT.  PKHT KNOWN TO AT LEAST EHT PERCENT
      EHT = 30.0
      ERHT = 100.0 * SQRT(TBK(LHT) + 2.0 * TBL(LHT)/PTS) /TBK(LHT)
      IF (ERHT - EHT) 2002,2002,2000
 2002 CONTINUE
C     CALC. OF PK. PARAMETERS, NL AND NR ARE LEFT AND RT SIDES OF THE PEAK.
C     NL, AND NR ARE THE CH NOS. AT WHICH THE TBK ARRAY IS ZERO.
      NL = LHT - 1
 2005 IF (TBK(NL)) 2003,2003,2004
 2004 NL = NL - 1
      GO TO 2005
 2003 CONTINUE
      NR = LHT + 1
 2008 IF (TBK(NR)) 2006,2006,2007
```

```
 2007 NR = NR + 1
      GO TO 2008
 2006 CONTINUE
C     MULTIPLET  IDENTIFICATION.
      LHTLO = WT(2099 + I)
      LHTUP = WT(2101 + I)
C     THE CENTERS NEXT TO THE I-TH PEAK ARE CHECKED, IF THE MULTIPLET
C     CONTRIBUTES MORE THAN 10 PERCENT TC THE I-TH PEAK HALF-HEIGHT
C     THE I-TH PEAK IS EXCLUDED FROM THE LSQ FIT.
      XL01 = FLOAT (LHT-LHTLC)/2.0
      XL12 = FLOAT (LHTUP-LHT)/2.0
C     BAD IS USED TO MARK THE MULTIPLETS FOR LATER IDENTIFICATION
      BAD = 0.0
      IF (LHTLO - NL) 2033,2010,2010
 2010 BAD = 1.0
      VRNC = (FPS/(2.355*SLP))**2
C     VRNC IS AN APPROXIMATE VALUE OF THE VARIANCE FOR THIS CALCULATION
      C = EXP (-(XL01**2)/(2.0*VRNC))
C     IF THE CONTRIBUTION FROM A NEARBY PEAK TO THE HALF-HEIGHT
C     OF THE PEAK UNDER CONSIDERATION IS MORE THAN 10 PERCENT
C     THE PEAK IS EXCLUDED FROM THE LSQ FIT.
      IF (TBK(LHTLO)*C/(0.5*TBK(LHT)) - 0.10) 2033,2033,2000
 2033 IF (LHTUP - NR) 2011,2011,2009
 2011 BAD = 1.0
      VRNC = (FPS/(2.355*SLP))**2
      D = EXP (-(XL12**2)/(2.0*VRNC))
      IF (TBK(LHTUP)*D/(0.5*TBK(LHT)) - 0.10) 2009,2009,2000
 2009 CONTINUE
C
C     EVALUATION OF AREA UNDER THE PEAK
      AREAS = 0.0
      DO 2012 K = NL,NR
      AREAS = AREAS + TBK(K)
 2012 CONTINUE
```

```
C       PCNR IS CALC. PEAK CENTER
        L1 = LHT
        PCNR = FLOAT (L1) + DTS(L1)/(DTS(L1-1) - DTS(L1)) + 0.5
              CALL ADJUST (CNTR,CORR,PCNR,TPC)
        EGAM = EGAM1 + SLP*(TPC - TPC1)
        LY = LHT
        PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
       1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
C       EVALUATION OF THE ERROR IN AREAS
        BKAV = TBL(LHT)
        PKWID = FLOAT(NR-NL)
              CALL EARS (BKAV,PTSAV,PKWID,AREAS,ERAS)
C
C       EVALUATION OF THE MEAS FWHM, AND THE S.D. IN ITS VALUE.
        GX = 0.5*PKHT
        NWL = LHT
 2015   IF (TBK(NWL) - GX) 2013,2014,2014
 2014   NWL = NWL - 1
        GO TO 2015
 2013   CONTINUE
        NWR = LHT
 2018   IF (TBK(NWR) - GX) 2016,2017,2017
 2017   NWR = NWR + 1
        GO TO 2018
 2016   CONTINUE
              CALL MWIDTH (TBK,TBL,GX,SLP,NWR,NWL,FWM,ERWMS,ERWM)
C       SUBROUTINE MWIDTH CALCULATES THE MEASURED FWHM, THE S.D. IN THE
C       MEASURED FWHM, AND S.D. SQUARED.
C       FWM IS FWHM IN KEV.
C       ERWMS IS THE S.D. OF FWM SQUARED.
C       FWHM IS THE FWHM IN KEV.
C
C       ACCEPTABLE FWHM CONDITION.
        AFWM = ABS(FWM - FPS)
```

```
C       ERFW IS THE ALLOWABLE DEVIATION OF THE FWHM (KEV).
        DFWM  = ERFW
        IF (AFWM - DFWM) 2019,2019,2000
 2019 CONTINUE
C       FPS IS RECALCULATED USING ITS OLD VALUE AND THE FWHM OF THE PRESENT PEAK.
        FPS = (FPS + FWM)/2.0
C       STORING THE PEAK PARAMETERS FOR I-TH PEAK WT(2100+I)= PK.LOC.
        WT(2500 + I) = EGAM
        WT(2900 + I) = PCNR
        WT(3300 + I) = GX
        WT(3700 + I) = AREAS
        WT(1700 + I) = ERAS
        WT(1300 + I) = FWM
        WT( 900 + I) = ERWM
        WT( 500 + I) = PKWID
C
C       AREA COMPUTATIONS
        AREAG = 2.1289 * FWM * GX / SLP
C       ARAT IS THE RATIO OF THE SUM TO GAUSSIAN AREA.
        ARAT = AREAS/AREAG
C       MULTIPLETS ARE EXCLUDED
        IF (BAD) 2020,2020,2021
 2020 CONTINUE
C       AREAS MORE THAN 30 PERCENT OFF ARE EXCLUDED.
        IF (ABS(ARAT-1.0) - 0.30) 2022,2022,2021
 2022 AREAGG = AREAGG + AREAG
        AREASS = AREASS + AREAS
 2021 CONTINUE
        MM = MM + 1
        WEIT = 1.0 / ERWMS
C       WEIT IS USED TO WEIGHT THE RESIDUALS**2 IN LSQ FIT.
        WRITE (JPRINT,2023) MM, I, EGAM, FWM, ERWM, WEIT, PKHT, ARAT
 2023 FORMAT (' ',4X,2I6,1X,F10.2,F10.3,F10.4,E10.3,F10.2,2X,F10.3)
C
```

```
C     LSQ COMPUTATIONS
      EGM = EGAM/1000.0
      WE0 = WE0 + WEIT*FWM
      WE1 = WE1 + WEIT*FWM*EGM
      WE2 = WE2 + WEIT*FWM*EGM*EGM
      E0  = E0 + WEIT
      E1  = E1 + WEIT*EGM
      E2  = E2 + WEIT*EGM*EGM
      E3 =  E3 + WEIT*EGM*EGM*EGM
      E4  = E4 + WEIT*EGM*EGM*EGM*EGM
      GO TO 2000
C
C     END OF LOOP FOR FITTING FWHM TO E.
 2100 CONTINUE
C     INVERTING E MATRIX TO GET D MATRIX.
      DENOM = E0*(E2*E4-E3*E3) - E1*(E1*E4-E2*E3) + E2*(E1*E3-E2*E2)
      D11 = (E2*E4 - E3*E3)/DENOM
      D22 = (E0*E4 - E2*E2)/DENOM
      D33 = (E0*E2 - E1*E1)/DENOM
      D12 = (E2*E3 - E1*E4)/DENOM
      D13 = (E1*E3 - E2*E2)/DENOM
      D23 = (E1*E2 - E0*E3)/DENOM
C     EVALUATIONS OF COEFFICIENTS
      A0 = D11*WE0 + D12*WE1 + D13*WE2
      A1 = D12*WE0 + D22*WE1 + D23*WE2
      A2 = D13*WE0 + D23*WE1 + D33*WE2
C     CALCULATION AND PRINT OUT OF LSQ DATA AND TESTS FOR FIT.
      WRITE (JPRINT,2024)
 2024 FORMAT ('1',' PK NO ENERGY KEV    W MEAS    W CALC       RSD    RS
     1D SQ RSD SQ WT')
      S = 0.0
      SS = 0.0
      ARATT = AREASS/AREAGG
      DO 2025 K = 1,NUMPK
```

```
      IF (WT(2500+K)) 2025,2025,2028
 2028 CONTINUE
      FW = WT(1300+K)
      EG = WT(2500+K)
      WEIT = 1.0/(WT(900+K)*WT(900+K))
      EGM = EG/1000.0
      CFW = A0 + A1*EGM + A2*EGM*EGM
      RSD = FW - CFW
      RSDS = RSD*RSD
      RSDW = WEIT * RSDS
      WRITE (JPRINT,2026) K,EG,FW,CFW,RSD,RSDS,RSDW
 2026 FORMAT (' ',1X,I5,1X,2(F10.2),4(F10.4))
      S = RSDW + S
      SS = RSDS + SS
 2025 CONTINUE
C
      MF = MM - 3
      WRITE (JPRINT,2027)
 2027 FORMAT ('1',4X,'EQUATION OF LEAST SQUARE FITTED FWHM TO A PARABOLA
     1 IN ENERGY')
      WRITE (JPRINT,2032) A0,A1,A2
 2032 FORMAT ('0',4X,'FWHM(KEV) = ',F9.3,' + ',F9.3,' * E(MEV) + ',F9.3,
     1 ' * E(MEV)**2 ')
      SDF = S/FLOAT(MF)
      EMS = SQRT(S/E0)
C     EMS IS THE RMS ERROR BETWEEN THE DATA FW AND CFW.
      WRITE (JPRINT,2029) MM,MF
 2029 FORMAT ('0',4X,'NUMBER OF PEAKS USED = ',I5,' DEGREES OF FREEDOM =
     1 ',I5)
      WRITE (JPRINT,2030) S,SDF
 2030 FORMAT ('0',4X,'S = SUM OF WEIGHT * RESIDUALS SQUARED = ',F10.3,
     1 ' USED IN CHI SQ TEST,  S/(N-P) = ',F10.3)
      WRITE (JPRINT,2031) EMS,ARATT
 2031 FORMAT ('0',4X,'RMS ERROR IN LSQ FIT = ',F8.4,' SUM OF AREAS/SUM O
```

```
     1F AREAG = ',F8.4)
C     INITIALIZING THE SUBROUTINE CWIDTH.
C     SUBROUTINE CWIDTH CALCULATES FWHM AND S.D. IN FWHM FROM THE
C     LSQ FIT AS DEVELOPED IN WIDLSQ.
C     PKANAL ENTERS CWIDTH AT ENTRY CWID AND USES FWC AND ERWC IN THE
C     PEAK ANALYSIS
      E = EGAM1
           CALL CWIDTH (A0,A1,A2,D11,D22,D33,D12,D13,D23,SDF,E,FWC,
     1 ERWC)
      RETURN
      END


      SUBROUTINE CWIDTH (AA0,AA1,AA2,AD11,AD22,AD33,AD12,AD13,AD23,ASDF,
     1 E,FWC,ERWC)
      A0 = AA0
      A1 = AA1
      A2 = AA2
      D11 = AD11
      D22 = AD22
      D33 = AD33
      D12 = AD12
      D13 = AD13
      D23 = AD23
      SDF = ASDF
      WRITE (6,2)
    2 FORMAT ('0',4X,'S.D. OF CALCULATED FWHM')
      WRITE (6,3) SDF;D11,D22,D33
    3 FORMAT ('0',4X,'S.D.(KEV) = ',E10.4,' * ( ',E10.4,' + ',E10.4,
     1 ' * E**2 + ',E10.4,' * E**4 ')
      WRITE (6,4) D12,D13,D23
    4 FORMAT (' ',30X,'+ ',E10.4,'*2.0*E + ',E10.4,'*2.0*E**2 + ',
     1 E10.4,'*2.0*E**3 )')
      ENTRY CWID (E,FWC,ERWC)
```

```
C      CALCULATING FWHM USING LSQ PARAMETERS.
       FWC = A0 + A1 * E + A2 * E * E
C      CALCULATING THE UNBIASED BEST ESTIMATE OF THE S.D. OF THE CALC.
C      VALUE OF THE FWHM.
       ERWC = (D11 + E*E*D22 + (E*E)*(E*E)*D33 +
      1 2.0*E*D12 + 2.0*E*E*D13 + 2.0*E*E*E*D23)*SDF
       RETURN
       END


       SUBROUTINE EARS (BKAV,PTS,PKWID,AREAS,ERAS)
C      SUBROUTINE EARS CALC. PER CENT ERROR IN SUM AREA.
C      BKAV IS AVERAGE BACKGROUND, PKWID IS WIDTH OF PEAK
C      AREAS IS SUM AREA, ERAS IS PERCENT ERROR IN AREAS.
C      ERAS*AREAS IS S.D. OF AREAS.
       ERAS = 100.C*SQRT(AREAS + BKAV*(PKWID-0.5 + PKWID*PKWID/PTS)/2.0)
      1 / AREAS
       RETURN
       END


       SUBROUTINE EARG (EFWC,FWH,PKHT,PTS,BKAV,ERAG)
C      SUBROUTINE EARG CALC. THE PERCENT ERROR IN THE GAUSSIAN AREA.
C      EFWC IS S.D IN FWHM FROM LSQ FIT.  FWH IS FWHM FROM LSQ FIT.
C      PKHT IS PEAK HEIGHT, PTS IS NO. OF PTS USED IN BAKSUB AV OF MINIMA.
C      BKAV IS AVERAGE BACKGROUND , AND ERAG IS PERCENT ERROR IN GAUS AREA.
       BKRAT = BKAV/(PTS*PKHT)
       ERAG = 100.0*SQRT(EFWC*EFWC/(FWH*FWH) + (1.0 + 2.0*BKRAT)/PKHT)
       RETURN
       END


       SUBROUTINE MWIDTH (TBK,TBL,GX,SLP,NR,NL,FWM,ERWMS,ERWM)
       REAL TBK(4096),TBL(4096)
```

```
C       SUBROUTINE MWIDTH CALCULATES THE MEASURED FWHM, THE S.D. IN THE
C       MEASURED FWHM, AND S.D. SQUARED.
C       FWM = FWHM IN KEV
C       ERWM IS THE S.D. OF FWHM IN KEV.
C       ERWM IS THE S.D. OF FWHM IN KEV.
    3   CONTINUE
        IF (TBK(NR-1) - TBK(NR)) 1,1,2
    1   NR = NR - 1
        GO TO 3
    2   CONTINUE
    4   CONTINUE
        IF (TBK(NL+1)-TBK(NL)) 5,5,6
    5   NL = NL + 1
    6   CONTINUE
C       CRG IS THE CORRECTION TERM TO THE RIGHT SIDE OF FWHM.
C       CRS IS THE CORRECTION TERM USED TO CALC THE S.D. OF FWHM. ON RT. SIDE.
C       CLG AND CLS ARE SIMILAR FOR LEFT SIDE OF PEAK
        CRG = (GX - TBK(NR))/(TBK(NR-1) - TBK(NR))
        CLG = (GX - TBK(NL))/(TBK(NL+1) - TBK(NL))
        SIGNR = SQRT(TBK(NR) + TBL(NR))
        SIGNL = SQRT(TBK(NL) + TBL(NL))
        SIGNR1 = SQRT(TBK(NR-1) + TBL(NR-1))
        SIGNL1 = SQRT(TBK(NL+1) + TBL(NL+1))
        CLS = (GX-TBK(NL)-SIGNL)/(TBK(NL+1)+SIGNL1-TBK(NL)-SIGNL)
        CRS = (GX-TBK(NR)-SIGNR)/(TBK(NR-1)+SIGNR1-TBK(NR)-SIGNR)
        FWM = (FLOAT(NR - NL) - CRG - CLG) * SLP
        ERWMS = ((CLG-CLS)*(CLG-CLS) + (CRG-CRS)*(CRG-CRS))*SLP*SLP
        ERWM = SQRT(ERWMS)
        RETURN
        END


        SUBROUTINE INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
       1                   TAREA,SINT,GINT,EFE)
```

```
      REAL EFFCY(200)
C     INTSTY FINDS THE EFFICIENCY OF THE SYSTEM AT THE GAMMA PEAK
C     ENERGY , EGAM, BY A SECOND ORDER INTERPOLATION USING THE EFFICIENCY
C     DATA IN THE EFFCY ARRAY AS THE KNOWN POINTS.
C     FIRENG IS THE FIRST ENERGY (KEV) VALUE USED IN EFFICIENCY CALC.
C     DELE IS THE ENERGY (KEV) DIFFERENCE BETWEEN EFFICIENCY POINTS.
C     SANGLE IS THE SOLID ANGLE CORRECTION TERM
C     FLUXT IS THE NUMBER OF CAPTURES/100 IN THE SAMPLE.
C     SAREA IS SUM AREA OF THE GAMMA PEAK.
C     TAREA IS THE GAUSSIAN AREA OF THE PEAK.
C     SINT IS THE INTENSITY OF THE SUM AREA.
C     GINT IS THE INTENSITY OF THE GAUSSIAN AREA.
C     EFE IS EFFICIENCY AT GAMMA ENERGY EGAM.
      IEGAM=2
    8 XEGAM = DELENG*FLOAT(IEGAM-1) + FIRENG
      IF (XEGAM-EGAM) 26,27,27
   26 IEGAM=IEGAM+1
      GO TO 8
   27 E1 = XEGAM - DELENG
      E2=XEGAM
      E3 = XEGAM + DELENG
      G1=EFFCY(IEGAM-1)
      G2=EFFCY(IEGAM)
      G3=EFFCY(IEGAM+1)
      D12=(G2-G1)/(E2-E1)
      D23=(G3-G2)/(E3-E2)
      D123=(D23-D12)/(E3-E1)
C     GX       SECOND ORDER INTERPOLATED EFFICIENCY AT GAMMA ENERGY EGAM.
      GX=G1+(EGAM-E1)*D12+(EGAM-E2)*(EGAM-E1)*D123
      EFE = GX
      SINT = SAREA/(GX*SANGLE*FLUXT)
      GINT = SINT * TAREA/SAREA
      RETURN
      END
```

```
      SUBROUTINE PKANAL (TBK,TBL,DTS,WT,CNTR,CORR,EFFCY,SLP,TPC1,EGAM1,
     1 ECR,ARATT,FIRENG,DELENG,SANGLE,FLUXT,PTS,NIPK,JPRINT,JPUNCH,
     2 IPUNCH)
      REAL TBK(4096),TBL(4096),DTS(4096),WT(4100),CNTR(200),CORR(200),
     1 EFFCY(100)
C
C     PEAK ANALYSIS  -  PEAKS THAT HAVE ALREADY BEEN ANALYSED ABOVE
C     HAVE THEIR PARAMETERS STORED IN THE WT ARRAY.
C
C     ALL TYPES OF PEAKS ARE CALCULATED IN TWO DIFFERENT WAYS
C       (A) AREA = SUM OF COUNTS IN ALL CHANNELS UNDER PEAK (SAREA)
C       (B) AREA = 1.0645*PEAK HEIGHT*FWHM*TERA WHERE THE TERM TERA
C           IS A CORRECTION FACTOR FOR THE NON-GAUSSIAN FORM OF THE
C           PEAKS AND FWHM IS THE LEAST-SQUARE-FITTED VALUE
C             CORRESPONDING TO THE PEAK ENERGY (TAREA)
      TERA = ARATT
      LCT = 0
      LPG = 0
      CALL PTOP(LCT,LPG)
C     SUBROUTINE PTOP PRINTS THE TOP OF THE PAGE HEADING FOR THE DATA.
C     CALCULATED IN PKANAL.
C     IPUNCH LESS THAN ZERO PUNCHES OUT PEAK ANALYSIS DATA
      IF (IPUNCH) 1237,1238,1238
 1237 CONTINUE
      WRITE (JPUNCH,1236)
 1236 FORMAT ('  NO. ENERGY(KEV) INT(GAUS)  PC ERR      AREAG      AREAS')
 1238 CONTINUE
C     I IS THE NUMBER OF THE PEAK AS SET BY THE PKLOC SUBROUTINE
C     N IS THE NUMBER OF THE PEAK PRINTED AND PUNCHED
      N = 1
      I = 0
      AVPTS = (PTS + 1.0)/2.0
```

```
      PTS = AVPTS
      NUMPK = NIPK
C     PTS IS RECALCULATED TO GIVE THE AVERAGE NO OF PTS USED TO AVERAGE
C     THE MINIMA IN THE CASE OF A STRONG PEAK.  PTS IS USED IN S.R. EARS
C     TO OBTAIN THE P.C. ERROR IN AREAS.
C     S.R. EARG CALC P.C.ERROR IN AREAG AND USES PTS ALSO.
C     SEE BAKSUB TO SEE HOW PTS IS USED TO AV MINIMA.
C
C     LOOP FOR PEAK ANALYSIS
 810  CONTINUE
      I = I + 1
      IF(I-NUMPK) 1856,1856,870
C     THE ZERO POINTS OF A PEAK ARE CALCULATED AGAIN FOR ALL PEAKS
 1856 J = WT(2100+I) - 1.0
  801 IF (TBK(J)) 802,802,803
  803 J = J - 1
      GO TO 801
  802 IA = J
C     IA IS ZERO POINT LOW ENERGY SIDE.
      J = WT(2100+I) + 1.0
 804  IF (TBK(J)) 805,805,806
 806  J=J+1
      GO TO 804
 805  IL=J
C     IL       IS ZERO POINT , HIGH ENERGY SIDE.
      L1 = WT(2100+I)
      L2 = WT(2101+I)
      L3 = WT(2102+I)
      L4 = WT(2103+I)
      XL12=FLOAT (L2-L1)
      XL23=FLOAT (L3-L2)
C     LOGIC TO DETERMINE IF THE PEAK DATA IS IN MULTIPLET FORM.
      IF (IL-L2) 811,811,812
 812  IF (IL-L3) 813,813,814
```

```
 814  IF (IL-L4) 815,815,816
C
C     SINGLET PEAK CALCULATION
  811 CONTINUE
C
C     CONDITION TO DETERMINE IF PEAK HAS BEEN USED IN EVALUATING THE
C         LSF FWHM IN THE PREVIOUS PART OF THE PROGRAM
      IF (WT(2500+I)) 1855,1855,1860
 1860 EGAM = WT(2500+I)
      GX = WT(3300+I)
      WIDTH = WT(1300+I)
      SAREA = WT(3700+I)
      PCNR = WT(2900+I)
      PKHT = 2.0*GX
      EGM = EGAM/1000.
C     FWH IS THE LSF FWHM OF THE PEAKS AT GIVEN ENERGY
C     AS CALC FROM LSQ FIT.
           CALL CWID (EGM,FWH,ERWC)
      TAREA = 2.1289*TERA*FWH*GX/SLP
           CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
     1                  TAREA,SINT,GINT,EFE)
C     FIRENG IS THE FIRST ENERGY (KEV) VALUE USED IN EFFICIENCY CALC.
C     DELE IS THE ENERGY (KEV) DIFFERENCE BETWEEN EFFICIENCY POINTS.
C     SANGLE IS THE SOLID ANGLE CORRECTION TERM
C     FLUXT IS THE TOTAL NUMBER OF NEUTRONS INCIDENT ON THE SAMPLE.
C     SINT AND GINT ARE SUM AND GAUSSIAN INTENSITIES.
C     EFE IS EFFICIENCY AT ENERGY EGAM
C
      ERAS = WT(1700+I)
      PKWID = WT( 500+I)
C     HTOB IS THE RATIO OF THE PEAK HEIGHT TO AN APPROXIMATE
C     VALUE OF THE BACKGROUND UNDER THE PEAK
C     THE ADDITIONAL 5.0 POINTS ARE TO INSURE THAT HTOB DOES NOT GO
C     TO INFINITY WHEN THE BACKGROUND GOES TO ZERO (END OF SPECTRUM)
```

```
      BKAV = TBL(L1)
      HTOB = PKHT/(BKAV + 5.0)
            CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
C     SUBROUTINE EARG CALC. THE PERCENT ERROR IN THE GAUSSIAN AREA.
C     EFWC IS S.D IN FWHM FROM LSQ FIT.  FWH IS FWHM FROM LSQ FIT.
C     PKHT IS PEAK HEIGHT, PTS IS NO. OF PTS USED IN BAKSUB AV OF MINIMA.
C     BKAV IS AVERAGE BACKGROUND , AND ERAG IS PERCENT ERROR IN GAUS AREA.
      WT( 100+I) = ERAG
      WT( 500+I) = SINT
      WT( 900+I) = GINT
      WT(3300+I) = PKHT
      LCT = LCT + 2
      IF (LCT.GT.34) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,1006) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
     1 EFE,PKWID
 1006 FORMAT (' ',20X,I3,F8.1,F7.1,F8.1,F8.4,F9.1,F6.1,F7.3,F7.2,E9.2,
     1 F4.0,' S *')
      WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
 4006 FORMAT (' ',54X,F9.1,F6.1,F7.3,F7.2)
      IF (IPUNCH) 1239,1240,1240
 1239 CONTINUE
      WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1235 FORMAT (I5,5F10.3)
 1240 CONTINUE
      N = N+ 1
      GO TO 810
C
C     ANALYSIS OF PEAKS NOT USED IN THE COMPUTATION OF THE LSF FWHM
C     AREA    IS AREA UNDER THE PEAK.
 1855 AREA = 0.0
      DO 807 K=IA,IL
 807  AREA=AREA+TBK(K)
      SAREA = AREA
C     ORT IS CALCULATED PEAK CENTER.
```

```
      ORT  = FLOAT (L1) + DTS(L1)/(DTS(L1-1)-DTS(L1)) + 0.5
      PCNR=ORT
      LY = L1
      PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
     1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
      BKAV = TBL(L1)
      HTOB = PKHT/(BKAV + 5.0)
      PKWID = FLOAT(IL-IA)
            CALL EARS (BKAV,PTS,PKWID,SAREA,ERAS)
C     SUBROUTINE EARS CALC. PER CENT ERROR IN SUM AREA.
C     BKAV IS AVERAGE BACKGROUND, PKWID IS WIDTH OF PEAK
C     PTS IS AV NO OF POINTS USED IN MINIMA AVERAGING.
C     AREAS IS SUM AREA, ERAS IS PERCENT ERROR IN AREAS.
C     ERAS*AREAS IS S.D. OF AREAS.
      IF (ERAS-ECR) 871,871,810
  871 CONTINUE
C     SUBROUTINE ADJUST CORRECTS PCNR TO OBTAIN THE TRUE PEAK CENTER
C             USING CNTR AND CORR FROM THE LINEARITY SUBROUTINE.
            CALL ADJUST (CNTR,CORR,PCNR,TPC)
C     EGAM    GAMMA ENERGY OF THE PEAK.
      EGAM=EGAM1+SLP*(TPC-TPC1)
C     EVALUATION OF LEAST-SQUARE-FITTED FWHM
      EGM = EGAM/1000.0
            CALL CWID (EGM,FWH,ERWC)
      GX = 0.5*PKHT
      TAREA = 2.1289*TERA*FWH*GX/SLP
C     EVALUATION OF ACTUAL FWHM
 1854 J = L1
  842 IF (TBK(J)-GX) 840,841,841
  841 J=J-1
      GO TO 842
  840 NL = J
      J=L1
  848 IF (TBK(J)-GX) 845,846,846
```

```
 846  J=J+1
      GO TO 848
  845 NR = J
          CALL MWIDTH (TBK,TBL,GX,SLP,NR,NL,WIDTH,ERWMS,ERWM)
C     WIDTH IS FWHM (KEV) AS MEAS.
C     SUBROUTINE INTSTY CORRECTS THE PEAK AREA FOR EFFICIENCY OF THE
C     SYSTEM AT ENERGY EGAM.
          CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
     1                 TAREA,SINT,GINT,EFE)
          CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
C     DATA OUTPUT
      WT( 100+I) = ERAG
      WT( 500+I) = SINT
      WT( 900+I) = GINT
      WT(1300+I) = WIDTH
      WT(1700+I) = ERAS
      WT(2500+I) = EGAM
      WT(2900+I) = PCNR
      WT(3300+I) = PKHT
      WT(3700+I) = SAREA
      LCT = LCT + 2
      IF (LCT.GT.34) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,1007) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
     1 EFE,PKWID
 1007 FORMAT (' ',20X,I3,F8.1,F7.1,F8.1,F8.4,F9.1,F6.1,F7.3,F7.2,E9.2,
     1 F4.0,' S ')
      WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
      IF (IPUNCH) 1241,1242,1242
 1241 CONTINUE
      WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1242 CONTINUE
      N = N + 1
      GO TO 810
C
```

```
C     DOUBLET PEAK CALCULATICN
C     THE PROCEDURE USED HERE IS SIMILAR TC THE SINGLET PEAK CALC.
C     TWO GAUSSIAN CURVES ARE FITTED TO THE DATA.
 813  AREA=0.
      DO 827 K=IA,IL
 827  AREA=AREA+TBK(K)
      PKWID = FLOAT(IL-IA)
      BKAV = (TBL(IL) + TBL(IA))/2.0
      CALL EARS (BKAV,PTS,PKWID,AREA,ERAS)
C     ERAS IS A FIRST APPROX TC THE P.C. ERROR IN THE MULTIPLET CASE.
C     FOR THE TOTAL SUM AREA UNDER THE MULTIPLET
C     ORT1    IS THE CALCULATED CENTER OF THE FIRST PEAK.
      ORT1 = FLOAT (L1) + DTS(L1)/(DTS(L1-1)-DTS(L1)) + 0.5
C     ORT2    IS THE CALCULATED CENTER OF THE SECOND PEAK.
      ORT2 = FLOAT (L2) + DTS(L2)/(DTS(L2-1)-DTS(L2)) + 0.5
C     AN AVERAGE FWHM IS CALCULATED FOR THE MULTIPLET IN ALL CASES
      PCNR = (ORT1 + CRT2)/2.0
           CALL ADJUST (CNTR,CORR,PCNR,TPC)
      EGAM = EGAM1 + SLP*(TPC-TPC1)
      EGM = EGAM/1000.
           CALL CWID (EGM,FWH,ERWC)
      WIDTH = FWH
      VRNC = (FWH/(SLP*2.35478))**2
      C=EXP (-(XL12**2)/(2.*VRNC))
C     L1      IS THE CHANNEL NUMBER OF THE MAXIMUM OF THE FIRST PEAK.
C     L2      IS THE CHANNEL NUMBER OF THE MAXIMUM OF THE SECOND PEAK.
      AREA1=AREA*(TBK(L1)-TBK(L2)*C)/((TBK(L1)+TBK(L2))*(1.-C))
      AREA2=AREA*(TBK(L2)-TBK(L1)*C)/((TBK(L1)+TBK(L2))*(1.-C))
      LY = L1
      DCOE = 1.0645*TERA*FWH/SLP
      DENOM = 1.0 - C**2
      PCNR = ORT1
      PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
     1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
```

```
      PKHT1 = PKHT
      PCNR = ORT2
      LY = L2
      PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
     1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
      PKHT2 = PKHT
C     FIRST PEAK DATA CALCULATION.
      PKHT = (PKHT1 - C*PKHT2)/DENOM
      IF (PKHT.LE.0.0) GO TO 892
            CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
      IF (ERAG - ECR) 872,872,892
 872  PCNR=ORT1
      TAREA = DCOE*PKHT
      SAREA=AREA1
      IF (SAREA.LE.0.0) GO TO 892
            CALL ADJUST (CNTR,CORR,PCNR,TPC)
      EGAM=EGAM1+SLP*(TPC-TPC1)
      HTOB = PKHT/(BKAV + 5.0)
            CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
     1                   TAREA,SINT,GINT,EFE)
      WT( 100+I) = ERAG
      WT( 500+I) = SINT
      WT( 900+I) = GINT
      WT(1300+I) = WIDTH
      WT(1700+I) = ERAS
      WT(2500+I) = EGAM
      WT(2900+I) = PCNR
      WT(3300+I) = PKHT
      WT(3700+I) = SAREA
      LCT = LCT + 2
      IF (LCT.GT.34) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,1008) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
     1 EFE,PKWID,C
1008  FORMAT (' ',20X,I3,F8.1,F7.1,F8.1,F8.4,F9.1,F6.1,F7.3,F7.2,E9.2,
```

```
     1 F4.0,' D ',F4.3)
       WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
       IF (IPUNCH) 1243,1244,1244
 1243  CONTINUE
       WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1244  CONTINUE
       N = N + 1
  892  I = I+1
C      SECOND PEAK DATA CALCULATION.
       PKHT = (PKHT2 - C*PKHT1)/DENOM
       IF (PKHT.LE.0.0) GO TO 810
             CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
       IF (ERAG - ECR) 873,873,810
  873  PCNR=ORT2
       TAREA = DCOE*PKHT
       SAREA=AREA2
       IF (SAREA.LE.0.0) GO TO 810
             CALL ADJUST (CNTR,CORR,PCNR,TPC)
       EGAM=EGAM1+SLP*(TPC-TPC1)
             CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
     1                    TAREA,SINT,GINT,EFE)
       HTOB = PKHT/(BKAV + 5.0)
       WT( 100+I) = ERAG
       WT( 500+I) = SINT
       WT( 900+I) = GINT
       WT(1300+I) = WIDTH
       WT(1700+I) = ERAS
       WT(2500+I) = EGAM
       WT(2900+I) = PCNR
       WT(3300+I) = PKHT
       WT(3700+I) = SAREA
       LCT = LCT + 2
       IF (LCT.GT.34) CALL PTOP(LCT,LPG)
       WRITE (JPRINT,1008) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
```

```
     1 EFE,PKWID,C
       WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
       IF (IPUNCH) 1245,1246,1246
 1245 CONTINUE
       WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1246 CONTINUE
       N = N + 1
       GO TO 810
C
C      TRIPLET PEAK CALCULATION
C      THE PROCEDURE USED HERE IS SIMILAR TO THE SINGLET PEAK CALC.
C      THREE GAUSSIAN CURVES ARE FITTED TO THE TRIPLET DATA.
C      AN AVERAGE FWHM IS CALCULATED FOR THE TRIPLET CASE.
 815   AREA=0.
       DO 837 K=IA,IL
 837   AREA=AREA+TBK(K)
       PKWID = FLOAT(IL-IA)
       BKAV = (TBL(IL) + TBL(IA))/2.0
       CALL EARS (BKAV,PTS,PKWID,AREA,ERAS)
       ORT1 = FLOAT (L1) + DTS(L1)/(DTS(L1-1)-DTS(L1)) + 0.5
       ORT2 = FLOAT (L2) + DTS(L2)/(DTS(L2-1)-DTS(L2)) + 0.5
       ORT3 = FLOAT (L3) + DTS(L3)/(DTS(L3-1)-DTS(L3)) + 0.5
       PCNR =(ORT1 + ORT2 + ORT3)/3.
             CALL ADJUST (CNTR,CORR,PCNR,TPC)
       EGAM = EGAM1 + SLP*(TPC-TPC1)
       EGM = EGAM/1000.
             CALL CWID (EGM,FWH,ERWC)
       WIDTH = FWH
       VRNC = (FWH/(SLP*2.35478))**2
       C=EXP (-(XL12**2)/(2.*VRNC))
       D=EXP (-(XL23**2)/(2.*VRNC))
       TBSM=TBK(L1)*(1.-D**2-C*(1.-D))+TBK(L2)*(1.-C-D)+TBK(L3)*
      1(1.-C**2-D*(1.-C))
       AREA1=AREA*(TBK(L1)*(1.-D**2)-TBK(L2)*C+TBK(L3)*C*D)/TBSM
```

```
      AREA2=AREA*(-TBK(L1)*C+TBK(L2)-TBK(L3)*D)/TBSM
      AREA3=AREA*(TBK(L1)*C*D-TBK(L2)*D+TBK(L3)*(1.-C**2))/TBSM
      TCOE = 1.0645*TERA*FWH/SLP
      DENOM = 1.0 - C**2 - D**2
      LY = L1
      PCNR = ORT1
      PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
     1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
      PKHT1 = PKHT
      LY = L2
      PCNR = ORT2
      PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
     1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
      PKHT2 = PKHT
      LY = L3
      PCNR = ORT3
      PKHT = TBK(LY) + (PCNR-FLOAT(LY)) * DTS(LY) +
     1 0.5 * (PCNR-FLOAT(LY))*(PCNR-FLOAT(LY+1))*(DTS(LY)-DTS(LY-1))
      PKHT3 = PKHT
C     FIRST PEAK DATA CALCULATION.
      PKHT = (PKHT1*(1.0-D**2)-PKHT2*C+PKHT3*C*D)/DENOM
      IF (PKHT.LE.0.0) GO TO 894
            CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
      IF (ERAG - ECR) 874,874,894
  874 PCNR=ORT1
      TAREA = TCOE*PKHT
      SAREA=AREA1
      IF (SAREA.LE.0.0) GO TO 894
            CALL ADJUST (CNTR,CORR,PCNR,TPC)
      EGAM=EGAM1+SLP*(TPC-TPC1)
      HTOB = PKHT/(BKAV + 5.0)
            CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
     1                   TAREA,SINT,GINT,EFE)
      WT( 100+I) = ERAG
```

```
      WT( 500+I) = SINT
      WT( 900+I) = GINT
      WT(1300+I) = WIDTH
      WT(1700+I) = ERAS
      WT(2500+I) = EGAM
      WT(2900+I) = PCNR
      WT(3300+I) = PKHT
      WT(3700+I) = SAREA
      LCT = LCT + 2
      IF (LCT.GT.34) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,1009) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
     1 EFE,PKWID ,C,D
 1009 FORMAT (' ',20X,I3,F8.1,F7.1,F8.1,F8.4,F9.1,F6.1,F7.3,F7.2,E9.2,
     1 F4.0,' T ',F4.3,1X,F4.3)
      WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
      IF (IPUNCH) 1247,1248,1248
 1247 CONTINUE
      WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1248 CONTINUE
      N = N + 1
  894 I = I + 1
C     SECOND PEAK DATA CALCULATION
      PKHT = (-PKHT1*C + PKHT2 - PKHT3*D)/DENOM
      IF (PKHT.LE.0.0) GO TO 895
            CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
      IF (ERAG - ECR) 875,875,895
  875 PCNR=ORT2
      TAREA = TCOE*PKHT
      SAREA=AREA2
      IF (SAREA.LE.0.0) GO TO 895
            CALL ADJUST (CNTR,CORR,PCNR,TPC)
      EGAM=EGAM1+SLP*(TPC-TPC1)
      HTOB = PKHT/(BKAV + 5.0)
            CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
```

```
     1                    TAREA,SINT,GINT,EFE)
      WT( 100+I) = ERAG
      WT( 500+I) = SINT
      WT( 900+I) = GINT
      WT(1300+I) = WIDTH
      WT(1700+I) = ERAS
      WT(2500+I) = EGAM
      WT(2900+I) = PCNR
      WT(3300+I) = PKHT
      WT(3700+I) = SAREA
      LCT = LCT + 2
      IF (LCT.GT.34) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,1009) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
     1 EFE,PKWID ,C,D
      WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
      IF (IPUNCH) 1249,1250,1250
 1249 CONTINUE
      WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1250 CONTINUE
      N=N+1
  895 I = I + 1
C     THIRD PEAK DATA CALCULATION.
      PKHT=(PKHT1*C*D-PKHT2*D+PKHT3*(1.0-C**2))/DENOM
      IF (PKHT.LE.0.0) GO TO 810
            CALL EARG (ERWC,FWH,PKHT,PTS,BKAV,ERAG)
      IF (ERAG - ECR) 876,876,810
  876 PCNR=ORT3
      TAREA = TCOE*PKHT
      SAREA=AREA3
      IF (SAREA.LE.0.0) GO TO 810
            CALL ADJUST (CNTR,CORR,PCNR,TPC)
      EGAM=EGAM1+SLP*(TPC-TPC1)
      HTOB = PKHT/(BKAV + 5.0)
            CALL INTSTY (EFFCY,EGAM,FIRENG,DELENG,SANGLE,FLUXT,SAREA,
```

```
     1                    TAREA,SINT,GINT,EFE)
      WT( 100+I) = ERAG
      WT( 500+I) = SINT
      WT( 900+I) = GINT
      WT(1300+I) = WIDTH
      WT(1700+I) = ERAS
      WT(2500+I) = EGAM
      WT(2900+I) = PCNR
      WT(3300+I) = PKHT
      WT(3700+I) = SAREA
      LCT = LCT + 2
      IF (LCT.GT.34) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,1009) N,EGAM,PCNR,PKHT,HTOB,SAREA,ERAS,SINT,WIDTH,
     1 EFE,PKWID ,C,D
      WRITE (JPRINT,4006) TAREA,ERAG,GINT,FWH
      IF (IPUNCH) 1251,1252,1252
 1251 CONTINUE
      WRITE (JPUNCH,1235) N,EGAM,GINT,ERAG,TAREA,SAREA
 1252 CONTINUE
      N=N+1
      GO TO 810
  816 CONTINUE
C
C     MULTIPLET PEAK ANALYSIS
C     MULPIPLETS WHICH ARE SO LABELED BECAUSE OF TINY PEAKS AT THE
C     WINGS OF STRONG ONES ARE ANALYSED AS TRIPLETS.  THE THREE
C     STRONGEST PEAKS IN THE MULTIPLET ARE CHOSEN FOR THAT PURPOSE.
C     THE SMOOTHED DATA SHOULD BE EXAMINED TO INSURE THIS.
C     FIRST 100 CHANNELS OF WT ARRAY AVAILABLE FOR MULTIPLET ANALYSIS.
      I3 = 2103 + I
C     EVALUATION OF II, THE NUMBER OF PEAKS IN THE MULTIPLET
 3034 CONTINUE
      IF (I3.GE.(2100+NUMPK)) GO TO 870
      LZ = WT(I3)
```

```
      IF (IL-LZ) 819,819,817
  817 I3 = I3 + 1
      GO TO 3034
  819 CONTINUE
C     UPON EXIT FROM IF STATEMENT I3 IS TOO LARGE BY ONE.
      II = I3 - 2100 - I
C     II IS THE TCTAL NUMBER OF MAXIMA BETWEEN CHS. IA AND IL.
C     E.G. WT(2103+I) IS THE LOCATION OF THE FOURTH MAXIMA BETWEEN IA AND IL.
C     LIMIT II TC BE .LE. 50.
      IF (II.GT.50) II = 50
C     ORDERING OF THE PEAKS IN TERMS OF DECREASING PEAK HEIGHT
      DO 3019 IE = 1,II
C     WT(2500+I) STORES THE ENERGY OF THE I TH PK.  IF THE MULTIPLET ANALYSIS
C     DROPS THIS MAXIMUM BECAUSE IT IS TOO WEAK, THEN THE ENERGY STORED
C     WILL BE ZERO.
      WT(2500 + I + IE - 1) = 0.0
      LS = WT(IE - 1 + 2100 + I)
      WT(IE) = TBK(LS)
      WT(IE + 50) = TBK(LS)
 3019 CONTINUE
C     LOOP 3020 ORDERS PK HT VALUES BY MAGNITUDE.
C     WT(IE) ARE THE PK HT VALUES ORDERED BY DECREASING VALUE.
C     WT(IE + 50) ARE THE PK HT VALUES IN ORDER THEY APPEAR.
      DO 3020 IP = 1,II
      DO 3020 IE = IP,II
      IF (WT(IP) - WT(IE)) 3021,3020,3020
 3021 ROK = WT(IE)
      WT(IE) = WT(IP)
      WT(IP) = ROK
 3020 CONTINUE
C     LOOP 3025 ORDERS THE FIRST THREE PEAK LOCATIONS IN ORDER OF DECREASING
C     PEAK HEIGHT.  DTS IS USED TO STORE THE THREE LOCATIONS TEMPORARILY.
      NR = 0
      DO 3025 NP = 1,3
```

```
      DO 3026 NQ = 1,II
      IF (WT(NP) - WT(NQ+50)) 3026,3027,3026
 3027 NR = NR + 1
      IV = NQ - 1 + 2100 + I
      DTS(NR) = WT(IV)
      GO TO 3025
 3026 CONTINUE
 3025 CONTINUE
C     ORDERING THE THREE STRONGEST PEAKS IN THE MULTIPLET BY INCREASING CH. NO.
      DO 3035 J = 1,3
      M = J + 1
      IF (J.EQ.3) GO TO 3035
      DO 3035 K = M,3
      IF (DTS(K) - DTS(J)) 3036,870,3035
 3036 DUM = DTS(K)
      DTS(K) = DTS(J)
      DTS(J) = DUM
 3035 CONTINUE
      L1 = DTS(1)
      L2 = DTS(2)
      L3 = DTS(3)
      XL12 = FLOAT (L2-L1)
      XL23 = FLOAT (L3-L2)
      LCT = LCT + 2
      IF (LCT.GT.32) CALL PTOP(LCT,LPG)
      WRITE (JPRINT,820) II
  820 FORMAT (' ',21X,'NUMBER OF MAXIMA IN MULTIPLET =',I4)
      WRITE (JPRINT,3033)
 3033 FORMAT(' ',21X,'THE 3 STRONGEST PEAKS ARE ANALYSED AS A TRIPLET.')
      I = I + II - 3
C     RETURN TO TRIPLET-PEAK ANALYSIS SECTION.
      GO TO 815
C
 870  CONTINUE
```

```
      RETURN
      END


      SUBROUTINE PTOP(LCT,LPG)
C     SUBROUTINE PTOP PRINTS THE TOP OF THE PAGE HEADING FOR THE DATA.
C     CALCULATED IN PKANAL.
      LCT = 4
      LPG = LPG + 1
      WRITE (6,1) LPG
    1 FORMAT ('1',////////////////22X,'PEAK ANALYSIS PAGE ',I3)
      WRITE (6,2)
    2 FORMAT (' ',20X,' NC  ENERGY PK CNT  HEIGHT  H TO B   AREA-S',
     1 ' ERR-S  INT-S FWHM-M  EFF(E) BASE TYPE')
      WRITE (6,3)
    3 FORMAT (' ',20X,'                                      AREA-G',
     1 ' ERR-G  INT-G FWHM-C')
      WRITE (6,4)
    4 FORMAT (' ',20X,'        KEV  CH NO  COUNTS   RATIO   COUNTS',
     1 '  PCSD N/100C    KEV  N/CTS  CHAN')
      RETURN
      END
```

TABLE H-3 GAMABC INPUT DECK EXAMPLE.

```
CARD
NUMBER
1     //G.SYSIN  DD *
2     11152   94   15   80 30.0    0
3              1          131.86          -31.71
4              2          161.24          -18.28
5              3          196.74          -10.98
               4          235.76           -7.20

      C     LINEARITY CORRECTION FACTORS FOR 94 PEAKS. AS PREVIOUSLY CALC.

92             91         3950.59            1.76
93             92         3993.34            1.82
94             93         4036.38            1.58
95             94         4079.08            1.68
96       0.     0 0.00 0.00    0.     0 0.00 0.00
97       191000. 500.
98     0.100E-06 1.010E-04 2.595E-04 4.225E-04 5.910E-04 7.422E-04 8.641E-04
99     9.061E-04 9.314E-04 9.275E-04 9.149E-04 8.751E-04 8.130E-04 7.231E-04
100    6.370E-04 5.499E-04 4.580E-04 3.695E-04 2.808E-04
101   11211 4095  226  2.0 30.0  3.0    0  7.0 1.585E-05 2.200E.11    1
102              0.    0.    0.    0.    0.    0.    0.     7
103        0.    0.    0.    0.    0.    0.    0.    0.    15
104        0.    0.    0.    0.    0.    0.    0.    0.    23
105        0.    0.    0.    0.    0.    0.    0.    0.    31

      C     GAMMA SPECTRA DATA DECK CHANNELS 1 TO 4095
                        512 CARDS

610        1.    0.    0.    0.    0.    0.    0.    0.  4071
611        1.    1.    1.    0.    1.    1.    1.    1.  4079
612        1.    1.    0.    0.    0.    0.    0.    1.  4087
613        0.    0.    0.    1.    1.    0.    0.    0.  4095
614     2223.3       586    7278.8       2990       8.00       4.00
```

TABLE H-3 GAMABC INPUT DECK EXAMPLE. (CONTINUED)

```
CARD
NUMBER
615   11271 4095     6018.8      390.0     7631.7     1020.0     7645.9      923.0 3.00
616              0.      0.      0.      0.      0.      0.      0.      7
617        0.    0.      0.      0.      0.      0.      0.      0.     15
618        0.    0.      0.      0.      0.      0.      0.      0.     23
619        0.    0.      0.      0.      0.      0.      0.      0.     31

C      GAMMA SPECTRA BACKGROUND DECK CHANNELS 1 TO 4095
                        512 CARDS

1124       0.    0.      0.      0.      0.      0.      0.      0.   4071
1125       0.    0.      0.      0.      0.      0.      0.      0.   4079
1126       0.    0.      0.      1.      0.      0.      0.      0.   4087
1127       1.    0.      0.      0.      1.      0.      0.      0.   4095
1128    2223.33      2.080     591.00    16     1.3500     0.0014 3.00     0
1129     1533.1  259  267       55.0        68.0       192.7
1130     2223.3  588  595       71.0        65.0       197.5
1131     4219.1 1546 1556       59.0        48.0       136.6
1132     4810.3 1831 1840       43.0        41.0       142.6
1133     5824.0 2318 2328       34.0        35.0       238.2
1134     5920.0 2365 2377       22.0        39.0       459.7
1135     6018.8 2411 2421       26.0        34.0       387.8
1136     7278.8 3018 3031       21.2        15.3       205.8
1137     7367.7 3100 3105       18.0        19.0        50.0
1138     7631.7 3184 3195       18.5        19.0      1023.0
1139     7645.8 3196 3207       19.0        19.6       920.0
1140     7723.8 3233 3242       12.0        15.0       220.3
1141     7915.0 3300 3305        3.0         3.0        50.0
1142     8485.7 3595 3598        1.0         1.0        10.0
1143     8887.5 3788 3790        1.0         1.0        10.0
1144     9297.4 3984 3999        0.0         0.0       107.4
1145     250.00    7480.00   0.00140 3.00    10
1146     0
/*
```

Table H-4

GAMABC Input Deck Description

Card Number	Variable Names FORMAT
1	LR, NOCHAN, N2, N3, XN, LIN (4I5, F5.0, I5)
2 - 95	CNTR(I), CORR(I), I = 1,NOCHAN (19X, F7.2, 9X, F7.2)
96	SIG1, MWTL01, WTC1, WTF1, SIG2, MWTL02, WTC2, WTF2 (F5.0, I5, 2F5.2, F5.0, I5, 2F5.2)
97	J2, FIRENG, DELENG (I5, 2F5.0)
98 - 100	EFFCY(I), I = 1,J2 (7(E10.3))
101	NUMRUN,NOCHAN,IMAX,DCR,ECR,BGER,IPUNCH,PTS, SANGLE,FLUXT,NOUT (3I5,3F5.1,I5,F5.1,2E10.4,I5)
102 - 613	TBK(I),I = 1,NOCHAN (7X,7(F6.0,1X)/(8(F6.0,1X)))
614	EGAM1,IP1,EGAM2,IP2,FPS,ERFW (4X,F6.1,4X,I6,4X,F6.1,4X,I6,3X,F7.2,3X,F7.2)
615	NBRUN,NBCHAN,E1,ARB1,E2,ARB2,E3,ARB3,DE (2I5,6F10.1,F5.2)
616 - 1127	DATBK(I), I = 1,NBCHAN (7X,7(F6.0,1X)/(8(F6.0,1X)))
1128	EGAMB1, SLPB, TPCB1, NSBKP, FAC, PKBFAC, PFAC, MPUN (F10.2,F10.3,F10.2,I5,2F10.4,F5.2,I5)
1129 - 1144	ENGY,LOB,LUPB,BLO,BLUP,ABK for NSBKP background peaks (F10.1,2I5,3F10.1)
1145	BINWID,BINDE,BINFAC,BPFAC,IWIT (2F10.2,F10.5,F5.2,I5)
1146	MO (I5)

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